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TELEOPERATOR TECHNOLOGY AND SYSTEM DEVELOPMENT

FINAL REPORT VOLUME I

APRIL 1972

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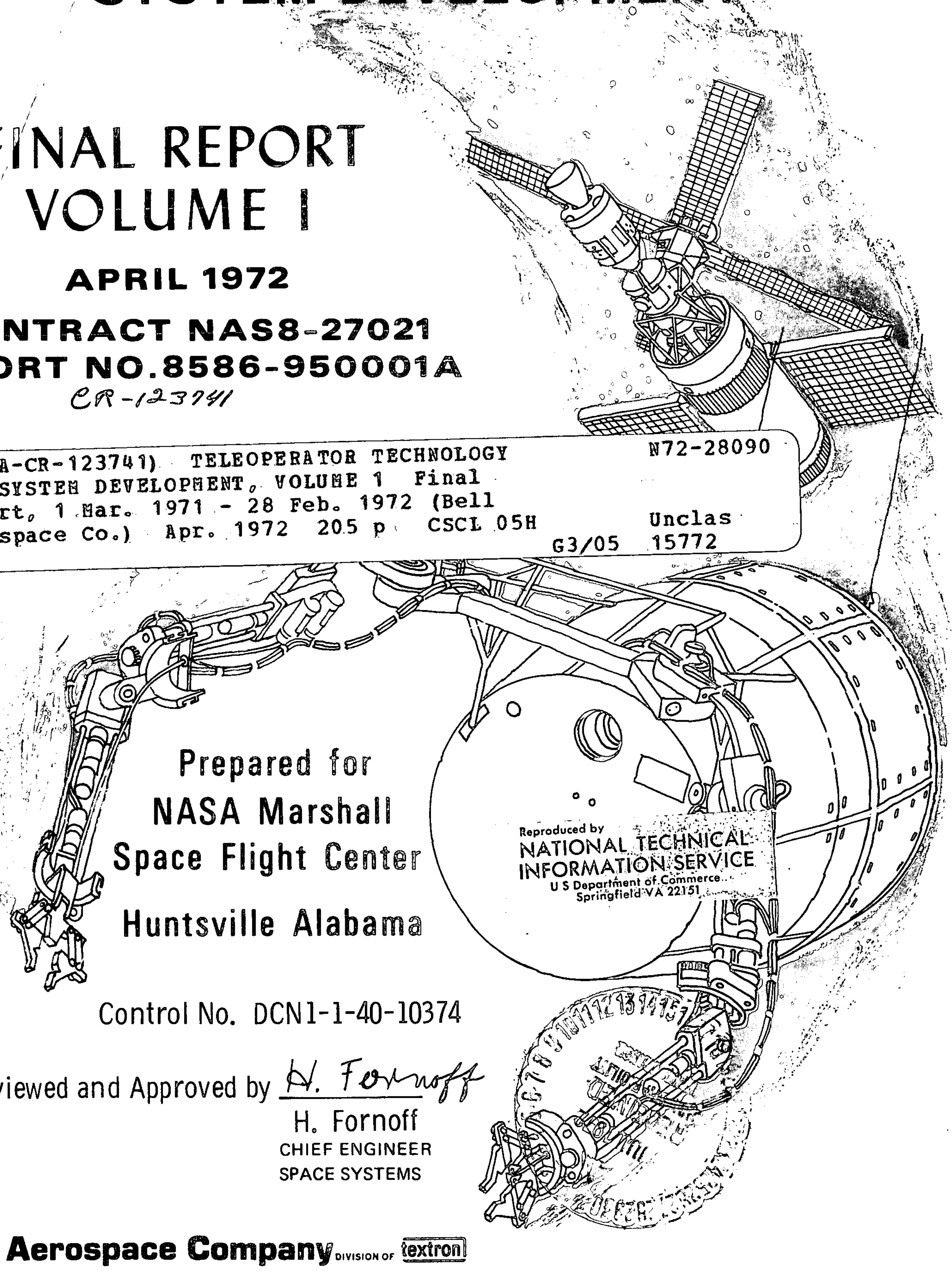

Prepared for
NASA Marshall
Space Flight Center

Huntsville Alabama

Control No. DCN1-1-40-10374

Reviewed and Approved by H. Fornoff
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SPACE SYSTEMS

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Report No. 8586-950001 A

TELEOPERATOR TECHNOLOGY AND SYSTEM DEVELOPMENT

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Prepared Under Contract NAS 8-27021 for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
ASTRIONICS LABORATORY
GEORGE C. MARSHALL SPACE FLIGHT CENTER

CONTROL NO. DCN 1-1-40-10374

FOREWORD

This report was prepared by Bell Aerospace Company under Contract NAS 8-27021, Teleoperator Technology and System Development for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. This work was administered under the technical direction of the Astrionics Laboratory of the George C. Marshall Space Flight Center with Mr. Wilbur S. Thornton as project manager. This is the Final Report on the contract, and it summarizes the technical effort from 1 March 1971 to 28 February 1972.

N. Economou was Project Manager for Bell Aerospace Company under the technical direction of Mr. H. Fornoff. J. Ridgway and J. Spencer participated in the conduct of the experiments and contributed to the analysis of results.

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ABSTRACT

A two phase approach was undertaken to:

1. Evaluate the performance of a general-purpose anthropomorphic manipulator with various controllers and display arrangements.

2. Identify basic technical limitations of existing teleoperator designs, and associated controls and displays.

3. Identify, through experimentation, the effects that controls and displays have on the performance of an anthropomorphic manipulator.

In Phase I the NASA-furnished manipulators, controls and displays were integrated with the Bell Remote Maneuvering Unit; in Phase II experiments were defined and performed to assess the utility of teleoperators for 6 typical space inspection, maintenance and repair tasks.

1.0 INTRODUCTION

Teleoperators, or remote manipulators can effectively extend man's capabilities for scientific exploration and extravehicular activities on future space missions. They can also physically replace man or augment his capabilities in the hostile environment of space. Teleoperator systems which have direct applications in these areas already exist and are being used in ground and undersea operations.

The primary objectives of this contractual effort have been:

(1) To evaluate teleoperator systems using an existing anthropomorphic manipulator and several controller/display combinations for performing typical space mission tasks.

(2) To identify inherent limitations of the 12-M type manipulator and to make recommendations on manipulator and worksite design that will permit maintenance and repair tasks to be performed by teleoperators.

To achieve these objectives the effort was divided into two phases. Phase I encompassed: (1) integration of NASA furnished manipulator arms, controllers and displays into the Bell 5 degree-of-freedom simulation facility, (2) design and fabrication of data links for remotely controlling the manipulator arms, and (3) fabrication of a task board fixture and work piece inserts for each space mission task. Phase II was an empirical program which accomplished: (1) the definition of teleoperator experiments representing a variety of maneuvering, docking and manipulative tasks that may be encountered in future space missions, and (2) the evaluation of the performance of the teleoperator systems of Phase I in accomplishing the experiments.

Figure 1 shows the facility and the equipment used in the empirical program. It includes the Bell 5 DOF simulation facility consisting of the Precision Floor (1), and Air Bearing Platform (2), a Remote Manuvering unit (RMU) (3), and a Flight Control Console (4). The RMU is a self-contained laboratory satellite with all subsystems required to simulate space maneuvering with a high degree of fidelity. It is maneuvered from the Flight Control Console. The task board (5), accepts six different work-piece inserts designed for the experiment program, and it provides a docking fixture representative of a passive spacecraft.

The NASA-furnished equipment includes the 12-M general-purpose anthropomorphic manipulators, three controllers, and two closed-circuit TV systems. The 12-M manipulator shown in Figure 2 was installed on and integrated with the RMU. This manipulator was designed and fabricated by the Rancho Los Amigos Hospital, Inc., and consists of a right and left arm, each having seven degreees-of-freedom.

The three controllers are:

1. Switch Controller - (6B) This controller commands a discrete ON signal to each manipulator joint which in turn drives it at its maximum rate.

2. Master Controller - (6A) An anthropomorphic exoskeleton controller which is donned by the operator. Each joint on the controller drives a corresponding joint on the manipulator arm. The control system incorporates proportional position control.

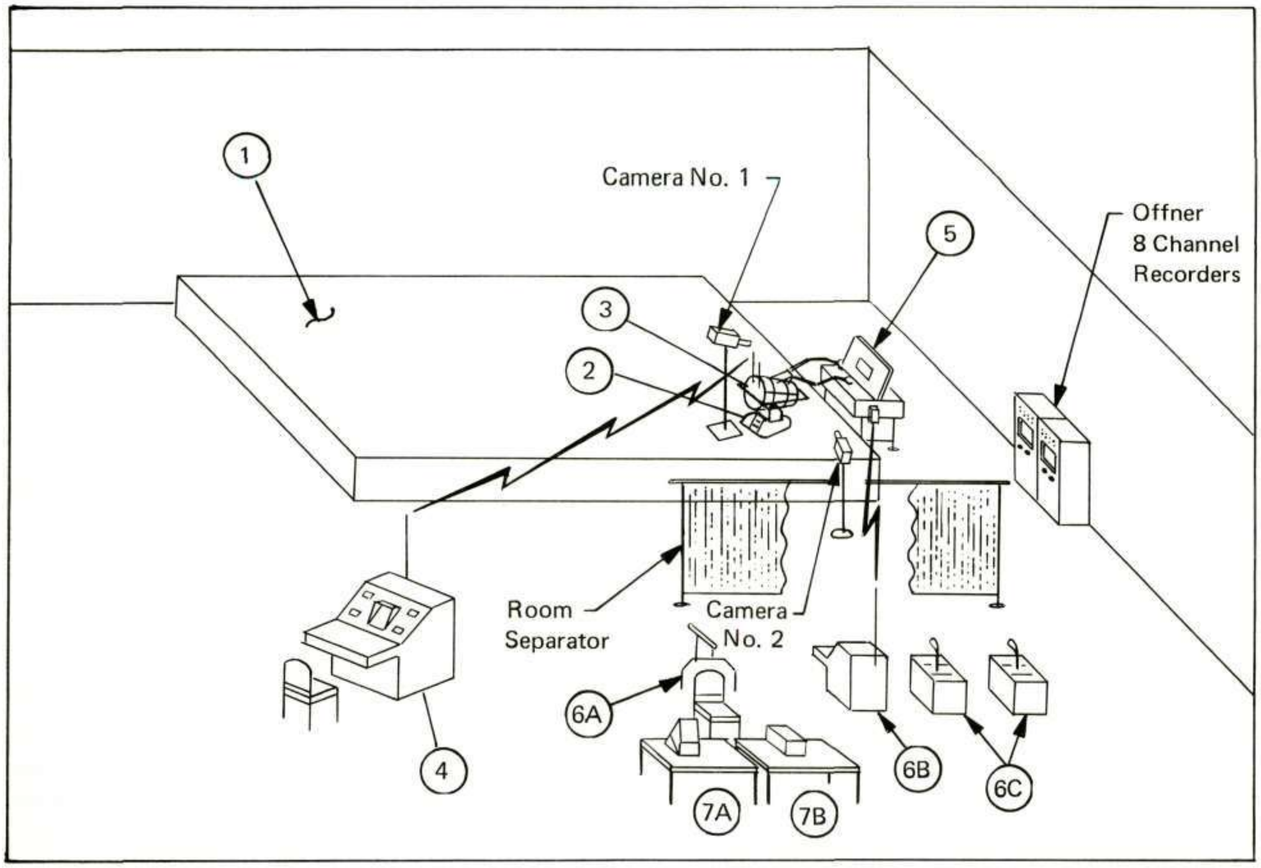

Figure 1. Simulation Facility

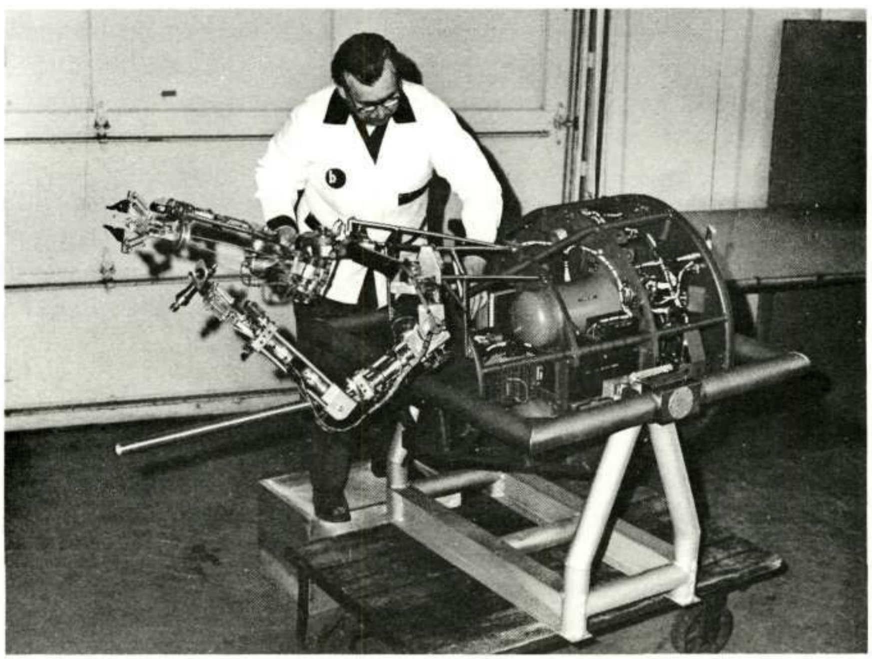

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Figure 2. Model 12-M General Purpose Anthropomorphic Manipulator

3. Levers - (6C) A joy-stick controller combining the position command system of the Master Controller for translational motions of the hand and selectable rate for the remaining joints.

The two closed-circuit TV systems (7a and 7b), whose camera location was varied during the experiment program, consist of a high resolution (940 line) system with remote pan and tilt controls, and a standard 525 line system. Both TV systems use the Angenieux L2 optics with 4:1 zoom capability and focus adjustments.

Detailed characteristics of equipment are documented in Appendix B of this report.

The experiments for the teleoperator performance evaluations were designed around a list of NASA-furnished general categories of projected in-space tasks. These included:

- Inspection
- Maintenance
- Mass Transfer
- Assembly
- Experiment Program Support.

Figure 3 describes six teleoperator experiments and relates each experiment to a general category of in-space task. Specific goals to be demonstrated objectively are listed on the right of this figure. In designing the work piece inserts, emphasis was placed on achieving the greatest degree of realism that could be tolerated by the experimental equipment. So, experiment design became an iterative process with both its configuration and procedure finalized in the pretraining qualification trials.

The experimental program encompassed two distinct types of simulation: (1) manipulation, and (2) maneuvering and docking. Both types of simulation required an operator to close the control loop, using visual displays as the only form of feedback.

In the manipulation experiments, controls and displays constituted the independent (system) variables. Significant variations in system performance were monitored by several dependent (performance) variables which measured:

- Total system activity, operator workload, thinking time
- Equipment duty cycles
- Ability to command continuous inputs
- Physical and mental workload
- Measures to add accuracy to speed of performance (errors).

In the maneuvering and docking experiments, displays, control dynamics and docking aids constituted the independent (system) variables. Accuracy of performance, speed, operator workload and energy expenditure were the dependent (performance) parameters.

The significant effects for both manipulation and maneuvering experiments were identified by analysis of variance, and relationships between system and performance parameters were established.

The data from three replications of each experiment were used to derive statistics for means and variances. All replications were performed by the same operator, a Bell Aerospace Test Pilot.

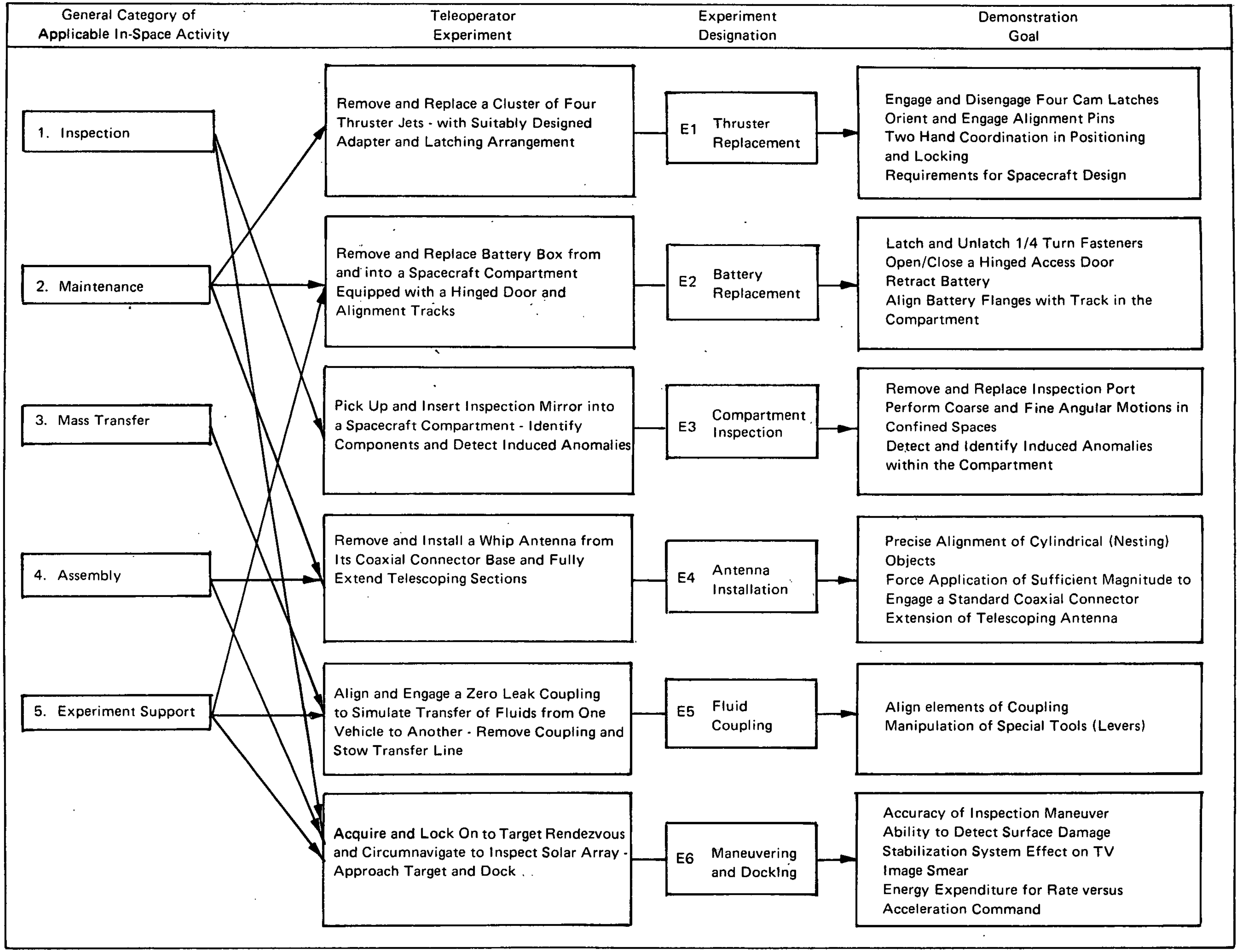

Figure 3. Experiment Selection

This operator was selected to represent the sector of population with a high degree of motor coordination – and is representative of subjects selected to participate in space flights.

A training program was formulated to ensure that no variation in performance of the operator is attributable to learning. The operator was trained until he achieved a level of consistency as determined by statistical "t" and "F" tests. Ten trials were selected as the minimum number required to obtain a reliable mean and variance.

The data recorded for manipulation experiments included a continuous trace of position versus time for each of the seven joints of each manipulator arm – and one channel for recording the errors at the instant of occurrence. These traces contained all information needed for assessing system performance using statistical techniques on a non-real time basis.

In maneuvering and docking experiments, data required to derive system performance were telemetered from the RMU as analog voltages and again recorded using continuous traces. To supplement data not readily attainable from the RMU, i.e., lateral deviations from the ideal path, an overhead camera was used to video tape each maneuver. These data were then reduced and suitably formulated in the analysis of variance matrices.

A multiple correlation analysis was performed to determine the extent to which dependent variables identified unique system parameters or mere duplications. The correlation coefficient matrices which were generated showed good independence among the monitored parameters both in the manipulation and maneuvering experiments.

CONCLUSIONS

The Conclusions drawn from the analyses are divided into two categories, General and Specific.

General Conclusion

The operator was able to perform all the tasks assigned to him with a great majority of the equipment combinations, but there were different levels of successful completion as indicated by the specific conclusions.

1. **Specific Conclusions for Manipulation**

    a. A single camera normal to the taskboard provided sufficient cues to permit successful completion of all experiments.

    b. Tasks requiring x-y alignment but lacking complete information in either x or y, displayed significant increases in operator workload (mental and physical).

    c. In situations where a second display is helpful, there is no clear-cut evidence in favor of either the 45° or 90° location with respect to the work piece.

    d. The use of a small mirror tilted at 45° to the task and affixed to the task board within the field of view of a single normal camera, yielded significant reduction in task completion time and workload over a single camera, and comparable results to an arrangement using two orthogonally placed cameras.

e. The three controls evaluated impose significantly different physical workloads; the Master Controller being most demanding, the Switch Controller the least demanding.

f. Significant differences in mental workload are indicated by the data – the Switch Controller being the most demanding and the Master Controller the least.

2. Specific Conclusions for Maneuvering and Docking

a. Range and Range Rate ($R\&\dot{R}$) display information reduces excursions in terminal velocity at docking and is deemed necessary to avoid excessive docking rates, which may be catastrophic. For teleoperator applications dockings should be made with a "positive" grappler not dependent on momentum exchange.

b. Attitude stabilization using rate command is superior to acceleration command systems.

c. Docking velocities are higher with a reticle than with the gunsight as docking aids.

d. Neither of the control dynamics investigated (acceleration and rate command) did in any way influence TV resolution or induce smear during stationkeeping inspection maneuvers.

e. There was no significant variation in fuel expenditure as a function of control mode. Electrical energy expenditure was significantly higher for the rate system.

3. Worksite Design Recommendations

a. Avoid use of conventional fasteners.

b. Hinged doors are preferable to completely removable ports.

c. Latches should engage and disengage with $< 60°$ rotation.

d. Shape handles to ensure positive indexing with manipulator terminal devices.

e. Enhance contrast of edges to aid alignment and provide visual cues.

f. Surfaces handled by manipulator should permit some flexure to relieve residual stresses.

g. Thruster and battery replacement should only be considered in the modular mode.

h. Provide guides for alignment which accommodate
   ±1/2 inch linear misalignment
   ±5 degrees angular misalignment

i. Avoid two-handed operations on a single module; design tasks so that they can be performed by a single arm.

2.0 EXPERIMENT PROGRAM

Current NASA plans include a wide spectrum of space station and shuttle related tasks which are appropriate for teleoperator applications. The list of general categories of tasks provided by NASA as potential candidates for formulating teleoperator experiments included:

- Inspection – of the exterior of spacecraft for punctures, breaks, fouled deployment mechanisms, degradation of surfaces or attached modules.
- Maintenance – of subsystems located external to the space station such as attitude control jet thrusters, deployment mechanisms, solar arrays, experiment modules, etc.
- Mass Transfer – transfer of large packages and fluids from shuttle to space station.
- Assembly – of subsystems such as station modules, large antennas, etc.
- Experiment Program Support – deployment and positioning of sensors and equipment either on the space station or remotely from it. Supply expendables and recover items in space for servicing or resupply.

An experiment program to demonstrate capability (or lack of it) in performing the many implied tasks within the above categories becomes prohibitively costly. Therefore, in order to bound the problem, the following program objectives were set forth:

(a) Demonstrate feasibility of a rendezvous and docking maneuver for the purpose of placing a remotely controlled teleoperator in a position to perform manipulative tasks.

(b) Demonstrate feasibility in performing a range of NASA space-mission related manipulative tasks with the docked teleoperator.

(c) Collect data on the salient aspects of task performance to allow analysis of the major variables affecting it.

Commensurate with these objectives and within the general NASA guidelines, six teleoperator experiments were defined. Figure 4 gives a brief description of each experiment and defines its primary demonstration goals. It also associates each experiment with one or more general categories of in-space activity.

Experiments E1 through E5 are designed to permit evaluation of manipulative tasks with the teleoperator docked to the work site. The last experiment, E6, was designed to demonstrate feasibility of rendezvous and docking with a stabilized target for the purpose of placing the teleoperator in position to perform the manipulative tasks.

The experimental program was defined in such a way as to allow systematic statistical evaluation of the effects of all independent variables (equipment comprising the system) and their interactions on all dependent variables (performance parameters).

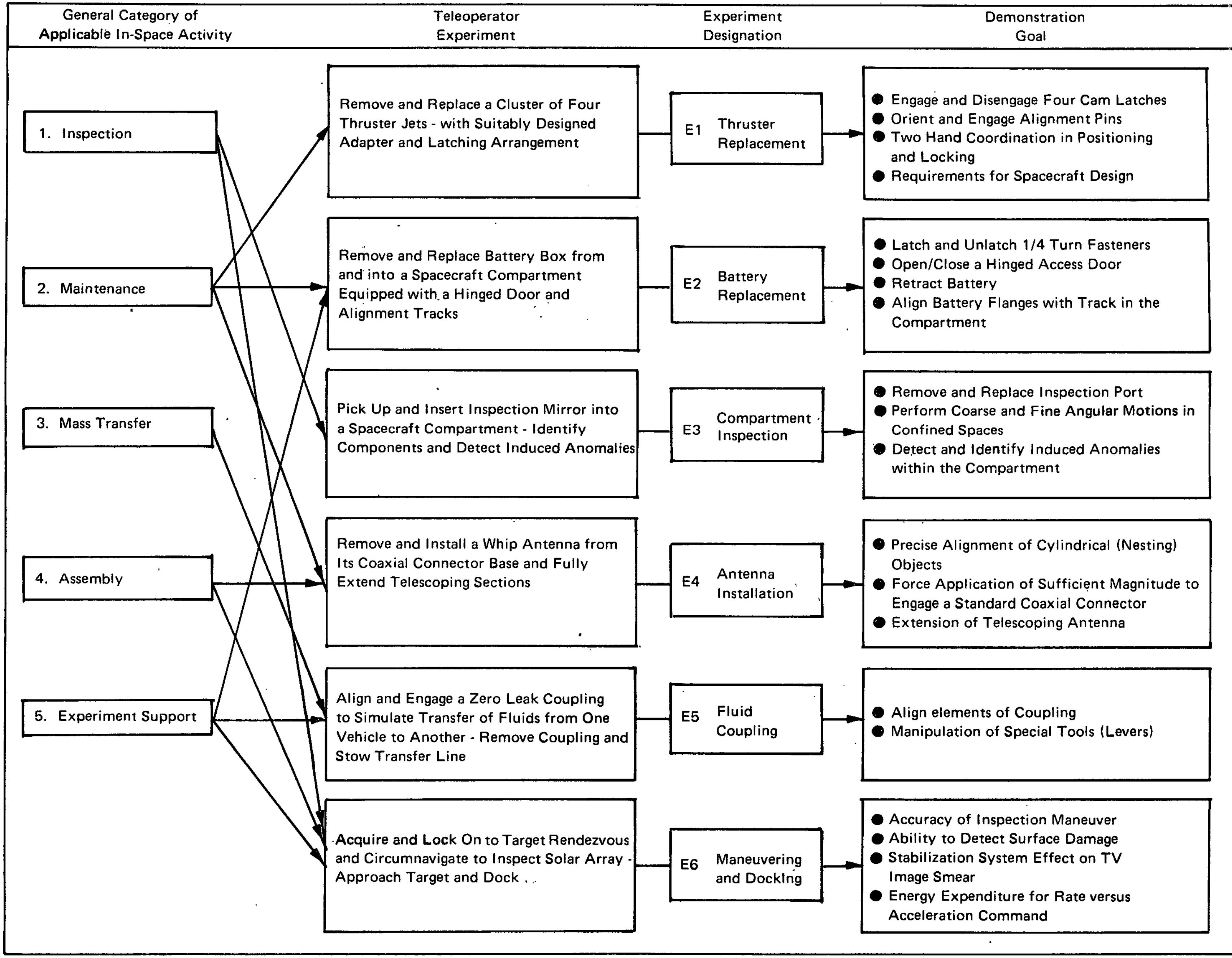

Figure 4. Experiment Selection

2.1 SELECTION OF VARIABLES

The following paragraphs identify the independent and the dependent variables defined for this program for the two distinct classes of simulation – manipulation and maneuvering/docking.

2.1.1 Manipulation Experiments (E1 through E5)

(a) Independent Variables

Displays and controllers constitute the independent variables for the manipulation experiments.

1. Displays – Viewing the workpiece from one or two different directions in order to provide a single view, orthogonal views or oblique views on two dimensional black and white monitors.

2. Controllers – Three types of controllers and associated control systems were subjected to evaluation. These are:

   Switches – "On-Off" controller which commands each joint of the manipulator at the maximum rate it can develop.

   Master – An exoskeleton controller utilizing a proportional position command system.

   Levers – A controller commanding position for translational motions and variable rate for rotary motions of selected joints.

(b) Dependent Variables

Many dependent variables for this study are task oriented. Dependent variables which can be generally applied to all manipulation tasks are:

1. Proficiency Measures – Time taken to perform tasks. This assumes no time limit for task performance. Such an arrangement would only be realistic if it is demonstrated that the task under investigation can be performed by the operator.

2. Integrated Joint Movement Time – A summation of the time during which each joint of the manipulation arm is moving in accomplishing a task. It is a measure of total system activity and is related to physical workload.

3. Integrated Joint-Off Time – A summation of the time, during accomplishment of a task, that the manipulator joints were at rest. This is considered to be a measure of thinking time.

4. Time Moved/Time Not Moved – A ratio of the above parameters which yields typical duty cycles for the manipulator components which result from use of various controller/display combinations.

5. Mean Duration of Joint Movement Time – This is primarily a controller evaluation measure indicating the ability of the operator to command continuous control inputs.

6. Mean Duration of Joint-Off Time – Another measure of thinking time required before issuing a command.

7. Total Number of Joint Actuations – The count of this number of control inputs made to each axis of control; an indicator of physical workload.

8. Subtask Times – This is a measure showing the sensitivity of speed of performance to changes in controls and displays.

9. Errors – A measure of performance to add accuracy to the speed and workload measures.

2.1.2 Maneuvering and Docking Experiment (E6)

(a) Independent Variables

The following classes of independent variables were controlled during the maneuvering and docking experiment.

1. Displays

Video – Use of a single video raster to display the image of a camera boresighted parallel to the vehicle's mean centerline. Controls for focus and 4:1 zoom adjustment are available to the operator.

Video + $R\dot{R}$ – The addition of range and range rate information to the TV display described above.

2. Control Dynamics

Direct – Acceleration command for attitude control with minimum impulse bit for translational commands.

Rate Command – For attitude with position hold feature using control moment gyros as the primary mode of attitude control.

3. Docking Aids

Gun Sight – Use of a reticle mounted on a boom extending forward of the vehicle and aligned with the camera line of sight. (See Figure 4a)

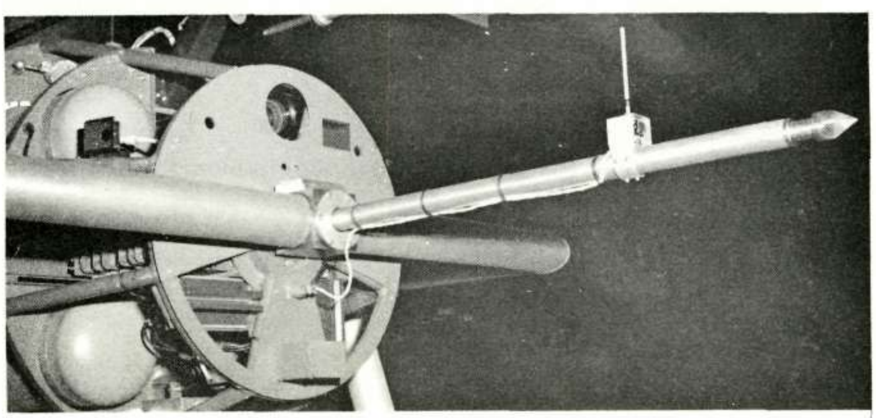

Figure 4a.

Reticle – A transparent film placed on the TV monitor incorporating cross hairs to permit alignment through visual cues only. (See Figure 4b)

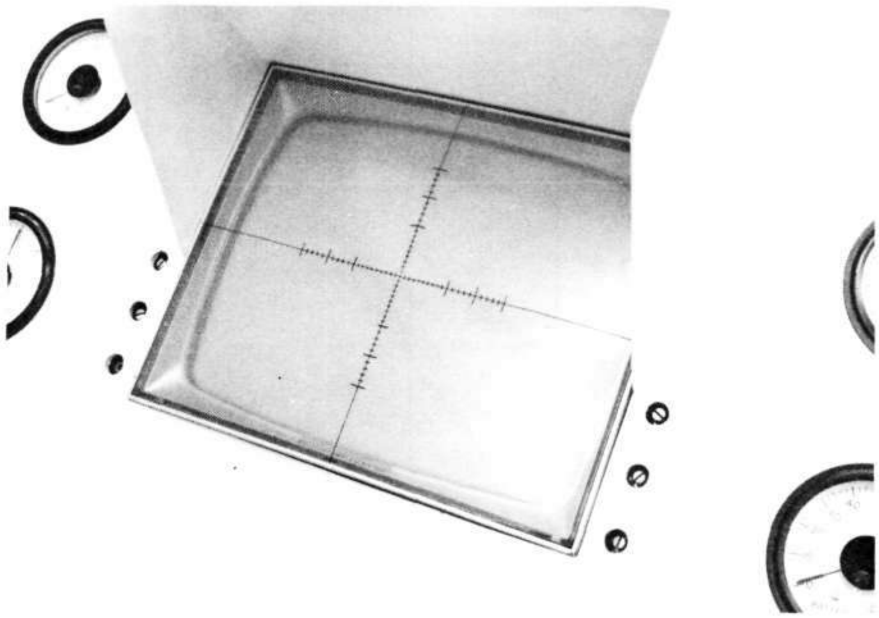

Figure 4b.

(b) Dependent Variables

The following basic sources of information are sought in the study for changes in the independent variables delineated above.

1. Speed of Performance – The time required to accomplish a given task or maneuver with velocity limitations.

2. Workload Imposed by Performance – The level activity required by the operator to control the vehicle.

3. Energy Expenditure – Propellant and Electrical Power dissipated in performing a task.

4. Accuracy of Performance – Mean and Extreme variations from the ideal path.

2.2 EXPERIMENT STRUCTURE

Following the definition of the experiment objectives, demonstration goals and performance variables, a detailed draft of each experiment was prepared. The draft included the description of the experimental apparatus and of the work piece, display arrangements, controller characteristics and step-by-step procedures for performing the task. Detailed descriptions for each of the six experiments performed are found in Appendix A. Characteristics of equipment used in the experiment program are contained in Appendix B.

A matrix of experimental runs was constructed and used during the experiment program. A typical matrix for manipulation experiments is shown in Table I. Each matrix represents

TABLE I
SUMMARY OF EXPERIMENT RUNS

			CONTROLLER TYPES		
		Replications	Switch Controller B_1	Master/ Controller B_2	Levers B_3
DISPLAYS	One camera bore-sighted on the task (Horizontal) A_1	R_1 R_2 R_3	$A_1B_1R_1$ $A_1B_1R_2$ $A_1B_1R_3$	$A_1B_2R_1$ $A_1B_2R_2$ $A_1B_2R_3$	$A_1B_3R_1$ $A_1B_3R_2$ $A_1B_3R_3$
	Two cameras at 90° boresighted on the task A_2	R_1 R_2 R_3	$A_2B_1R_1$ $A_2B_1R_2$ $A_2B_1R_3$	$A_2B_2R_1$ $A_2B_2R_2$ $A_2B_2R_3$	$A_2B_3R_1$ $A_2B_3R_2$ $A_2B_3R_3$
	One camera bore-sighted on the task (Vertical) A_3	R_1 R_2 R_3	$A_3B_1R_1$ $A_3B_1R_2$ $A_3B_1R_3$	$A_3B_2R_1$ $A_3B_2R_2$ $A_3B_2R_3$	$A_3B_3R_1$ $A_3B_3R_2$ $A_3B_3R_3$

27 experimental runs encompassing 3 display arrangements denoted by A1, A2 and A3, three types of controllers B1, B2 and B3 and three replications of each controller/display combination, designated R1, R2 and R3, were performed by the same subject.

Ordering effects were eliminated by randomly selecting each successive element of the matrix using a card drawing procedure.

2.2.1 Pretraining Qualification Tests

A series of pretraining qualification tests was performed with each completed task board to ensure: (1) that the tasks, as conceived and built for each experiment, can be performed with the available equipment and (2) verify that the established procedure changes identified from these tests, which either improved handling characteristics or reduced workload, were incorporated into the experiment prior to initiating the training program.

2.2.2 Operator Training

In order to ensure that the operator had been adequately trained, prior to the collection of experimental data, a special procedure was developed to determine whether performance with the system to be evaluated had reached asymptote.

To measure a learning process, it is necessary to choose some quantity that changes as the individual learns and that becomes statistically constant when he ceases to learn. For certain activities, one of the easiest and most useful quantities is the time it takes an individual to perform a particular task. To determine when the individual has ceased to learn, it is necessary to devise a statistical test that determines when the time to do a particular task is essentially constant.

The method devised accumulates samples from each learning trial (time to perform a particular task) until the mean of the quantity becomes constant with fixed variance.

Five trials were selected as the minimum number required to obtain a reliable mean and variance. Ten trials were therefore collected and the mean and variance of trials 1 through 5 compared with those of 6 through 10, using a t test and an F test respectively.

A significant difference in the t or F test with $\alpha \geqslant 0.05$ was grounds for inferring a continuing learning process, and a further trial was run and the first trial ignored; t and F tests were then performed to compare trials 2 through 6 with trials 7 through 11. This process continued until no significant difference of either F or t test could be obtained.

A computer program was written to perform the above method and was used successfully via a RAX terminal. Complete details of the assumptions and equations used in the training program and training curves for each experiment are presented in Appendix D.

2.2.3 Test Subject - Qualifications

A single subject was used throughout the series of experiments reported herein. This subject was a healthy male aged: 35, weight: 170 lb, height: 5 ft 8 inches.

His occupation is Manager, Flight Test Operations and Chief Test Pilot. He holds the degree of B.S. in Electrical Engineering and is a graduate of the Empire Test Pilot School, Farnborough, England. In addition to his work in this study, his experience includes the operation of rocket-powered small-lift devices in a variety of flight control configurations including kinesthetic control. He has also operated a 1/6 g moving base simulation of lunar handling characteristics.

His total flying hours are:

Jet	127	Helicopter	2,207
Reciprocating	868	V/STOL	77
Turboprop	5		

2.3 DATA COLLECTION

The instrumentation for the data collection effort was designed to provide a permanent record of the raw data gathered during the test program and to permit data reduction and analysis on a non-real time basis.

2.3.1 Data Recorded on Manipulation Experiments (E1 - E5)

Two synchronized eight-channel Offner recorders were used to provide a continuous record of the potentiometer voltages for each of the 14 joints in the right and left arm of the 12-M Manipulator. Angular displacement of each joint was recorded for the entire duration of the test. Seven channels of each recorder were assigned to record the following functions:

Channel 1	Shoulder Yaw	Channel 5	Wrist Pitch
Channel 2	Shoulder Pitch	Channel 6	Wrist Roll
Channel 3	Shoulder Roll	Channel 7	Hand
Channel 4	Elbow (Pitch)		

The eighth channel of each recorder was used to record the errors committed during execution of the task at the appropriate instant of occurrence.

Input voltages representing maximum joint deflection were ±5V. The maximum displacement was seldom used however. Depending on the task being performed, the test director changed the scale factors on the recorder to achieve the largest possible amplification. Appropriate scale factors for each run are documented on the recorder traces. The recorders were situated in close proximity to the test director to provide a real-time display of the operational status of all signals. Figure 5 shows a typical trace of the recorded data.

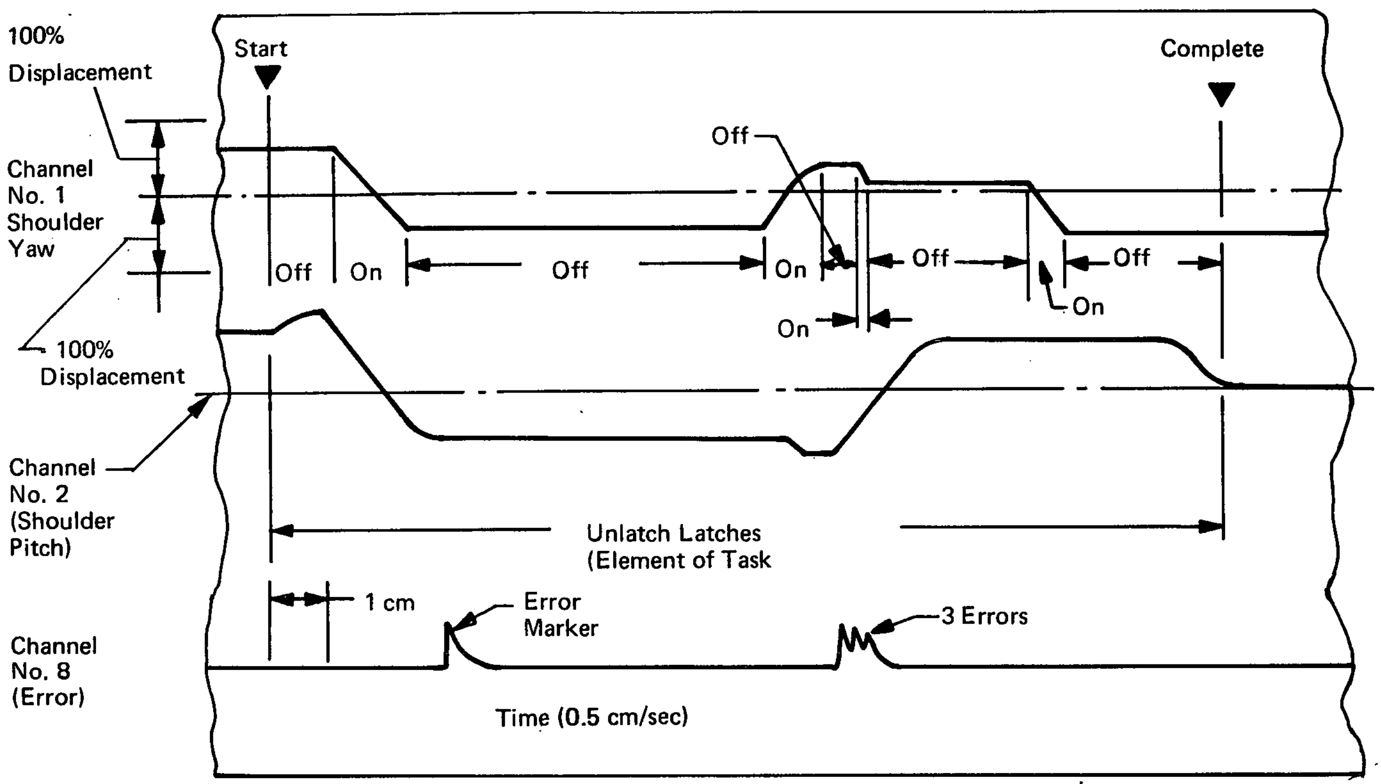

Figure 5. Typical Recorder Trace for Manipulation Task

Task and subtask durations were also derived from the recorder traces from markings placed on the record by the test conductor. The following workload and joint usage measures were derived from the recorded data.

Workload Measures

- Mean time an arm is moving
- Mean time between movements
- Integrated time arm is moving
- Integrated time between movements
- Time moved/time not moved

Joint Usage

- Use per trial (count the number of times each joint is used per trial).
- Total duration of joint usage (count total duration each joint is used during trial).
- Joint use/Total use-Ratio of total duration one joint is used to total duration all joints are used.

Use strip chart recorder. 14 channels 5mm/sec. Record manipulator potentiometer voltages versus time

2.3.2 Data Recorded for Maneuvering and Docking Tests

The techniques involved in the collection and recording of data for evaluation of maneuvering and docking tests varied considerably from those used for manipulation.

Flight vehicle body rates and displacements were the dependent variables for these experiments. To record these functions appropriate sensors were installed on the RMU vehicle and their outputs as analog voltages telemetered to the control console using the RMU data link. Because some of these same signals are used in the RMU control loop, (in R, $\dot{R}$), it was necessary to fabricate and install buffer electronics for each channel recorded for subsequent evaluation.

One eight channel Offner recorder was used to record the following functions:

Channel 1	Range	Channel 5	Pitch displacement
Channel 2	Range Rate	Channel 6	Roll displacement
Channel 3	Fuel	Channel 7	Not used
Channel 4	Battery Status	Channel 8	Used by test director to code phases of the maneuver

(a) Acquisition
(b) Translation
(c) Circumnavigation
(d) Inspection
(e) Docking approach

The two additional parameters needed for maneuvering and docking evaluation, Y-translation and vehicle yaw require extensive instrumentation to achieve. To overcome this difficulty, each run was video taped with a camera located above the precision floor. The ideal maneuver was outlined on the floor using 12-inch long dashed lines. (These lines were not seen by the operator.) By playing back the tape, the action could be stopped and the deviation in Y-displacement and vehicle yaw measured. Parallax problems were alleviated by using the dashed lines painted on the floor (see Experiment E6, Appendix A) as unit measures. Markings on the air bearing platform very close to the floor were used to determine angular measurements.

The following performance parameters were derived from the data recorded with the OFFNER and Video Tape.

- Fuel expenditure
- Battery expenditure
- Average range rate during translation
- Maximum range rate achieved
- Error in pitch, yaw and roll attitude
- Deviation from the ideal path during translation and circumnavigation maneuvers
- Total time required to accomplish the complete maneuver
- Instantaneous values of R & $\dot{R}$ at the instant the docking probe made contact

One additional parameter, lateral miss-distance during the docking maneuver was manually recorded. The test director also manually recorded work load performance parameters and significant comments of the operator concerning difficulty of control.

2.4 DATA ANALYSIS TECHNIQUES

The data from each experiment were entered into analysis of variance matrices and analyzed using a computer program entered via a RAX terminal. Table II shows a typical analysis of variance printout. The purpose of this analysis was to determine the existence or non-existence of statistically significant variation in teleoperator system performance as detected by each of the performance measures (dependent variables) for variations of the control and display systems. Throughout the analyses, displays are coded with an A and controls with a B.

All statistically significant effects, as identified by the analysis of variance, were plotted to show the nature of the functional relationships between independent (system) and dependent (performance) parameters. These relationships are expressed in terms of means, extremes and standard deviations. A complete set of plots for all significant effects are included in Appendix C.

Subjective assessments of the importance of each system parameter (controls and displays) were also collated for comparison with objective measures.

Finally, an analysis of the extent to which dependent variables identified unique aspects of system performance or merely duplicated information, was conducted using multiple correlation. A computer program employing the Pearson Product Moment Correlation Coefficient (Reference 1) was used to determine the extent to which each performance dependent variable correlated with every other. A typical correlation analysis is shown in Table III. The significance level α of each correlation coefficient r (depicted in the field of the matrix) was determined using the standard test:

$$t = \frac{r}{\sqrt{1 - (r)^2}} \quad (n - 1) \qquad n = \text{number of observations per variable}$$

Values of t for $\alpha = 0.05, 0.01$ and 0.001 were taken and three corresponding values of r computed. Each correlation coefficient was then compared with the three (3) values of r to determine its level of significance, and then simplified into the format of Table IV in order to facilitate decisions on which variables are most useful and which least useful as performance indicators.

TABLE II
A TYPICAL ANALYSIS OF VARIANCE PRINT OUT

```
ENTER   27 DATA OBSERVATIONS, SEPARATED BY COMMAS
14.75,17.90,21.66,6.56,7.25,5.37,10.64,13.04,9.61,
16.49,17.78,15.20,6.29,5.97,6.72,9.03,10.19,14.60,
17.67,17.57,14.78,7.08,6.75,6.50,9.65,12.38,13.34,

ANALYSIS OF VARIANCE.....JEP


LEVELS OF FACTORS
  A           3
  B           3
  R           3


GRAND MEAN           11.65814
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THRUSTER CLUSTER REMOVAL AND REPLACEMENT: INTEGRATED BETWEEN JOINT MOVEMENT TIME, RIGHT HAND IN MINUTES

SOURCE OF VARIATION	SUMS OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARES	F-STATISTIC	PROBABILITY
A	7.68501	2	3.84250	1.24488	0.6883841
B	505.66113	2	252.83057	81.91100	0.9999995 Significant
AB	8.27526	4	2.06882	0.67025	0.3789692
R	55.55971	18	3.08665		
TOTAL	577.18018	26			

TABLE III

A TYPICAL CORRELATION ANALYSIS - MANIPULATION EXPERIMENT

```
/id anov 073583818450500

M.0076 RAX IS IN CONTROL, SIGN ON.
/id anov 073583818450500
M.0073  ACTION IN PROGRESS
M.0072  BEGIN
/input
/include stat
/endrun



 IS A CORRELATION ANALYSIS DESIRED.(YES OR NO)
yes

INPUT THE NUMBER OF VARIABLES(M.LE.20) AND THE NO.OF OBSERVATIONS(N.LE.60).(M,N)

10,16

INPUT THE  16 OBSERVATIONS FOR EACH OF THE  10 VARIABLES.ONE SET OF OBSERVATIONS PER LINE


2.63,2.69,2.96,3.2,2.8,3.19,2.62,2.32,3.38,6.64,5.6,5.68,4.66,6.37,7.23,4.8,
7.52,7.15,
29.77,22.41,28.23,27.99,26.58,27.61,28.97,24.77,35.22,7.24,7.,7.15,7.94,6.58,
8.17,8.26,6.36,6.5,
.2,.12,.105,.114,.106,.115,.09,.094,.096,.917,.8,.794,.587,.969,.884,.581,
1.18,1.1,
1.066,1.214,1.304,1.264,1.183,1.485,1.111,1.043,1.308,3.068,2.361,1.753,
1.358,3.606,3.338,1.364,3.213,3.36,
13.547,10.311,13.108,12.584,11.779,14.423,13.908,10.857,15.905,3.388,3.215,
2.607,2.797,3.234,4.059,2.893,2.591,2.91,
272.,208.,243.,210.,244.,222.,250.,220.,256.,146.,159.,206.,212.,125.,147.,
226.,157.,143.,
2.08,2.23,2.27,2.28,2.47,2.58,2.43,2.47,2.9,1.,.9,1.07,.917,.88,.88,.933,.78,
.9,
3.32,1.95,2.93,2.91,2.5,2.55,2.83,2.05,3.53,.983;.0,.933,.883,.967,1.32,.933,
M.0064 LINE TOO LONG, RETRANSMIT.
3.32,1.95,2.93,2.91,2.5,2.55,2.83,2.05,3.53,.983,.9,.933,.883,.967,1.32,.933,
1.2,1.05,
3.,4.,3.,9.,5.,5.,5.,9.,8.,0.,1.,1.,1.,3.,2.,1.,2.,1.,
12.,7.,10.,9.,6.,6.,11.,6.,13.,1.,0.,2.,1.,3.,3.,3.,2.,5.,
```

CORRELATION COEFFICIENT MATRIX

	1	2	3	4	5	6	7	8	9	10	
1	1.0000										INTEGRATED JOINT MOVEMENT TIME
2	-0.8827	1.0000									INTEGRATED JOINT OFF TIME
3	0.9785	-0.9263	1.0000								TIME MOVED: TIME NOT MOVED RATIO
4	0.9233	-0.7423	0.8949	1.0000							MEAN DURATION OF JOINT MOVEMENT TIME
5	-0.8601	0.9938	-0.9105	-0.6984	1.0000						MEAN DURATION OF JOINT ''OFF'' TIME
6	-0.8684	0.8122	-0.8578	-0.9287	0.7726	1.0000					TOTAL NUMBER OR JOINT ACTUATIONS
7	-0.8904	0.9758	-0.9340	-0.7434	0.9729	0.7677	1.0000				SUBTASK 1 TIME
8	-0.7812	0.9739	-0.8362	-0.6408	0.9695	0.7722	0.9093	1.0000			SUBTASK 2 TIME
9	-0.6803	0.7840	-0.7295	-0.5289	0.7667	0.4805	0.8194	0.7239	1.0000		SUBTASK 1 ERRORS
10	-0.6803	0.7840	-0.7295	-0.5289	0.7667	0.4805	0.8194	0.7239	1.0000	1.0000	SUBTASK 2 ERRORS

TABLE IV
RESULTS OF ANALYSIS OF VARIANCE
MANIPULATION EXPERIMENTS E1 THROUGH E5

No.	Dependent Variables	E1 Thruster Replacement								
		Left Hand			Right Hand			Both Hands		
		A	B	AxB	A	B	AxB	A	B	AxB
1	Integrated Joint Movement Time	NS	***	NS	NS	***	NS	NS	***	NS
2	Integrated Joint OFF Time	NS	***	NS	NS	***	NS	NS	***	NS
3	Time Moved: Time Not Moved Ratio	NS	***	NS	NS	***	NS	NS	***	NS
4	Mean Duration of Joint Movement Time	NS	***	NS	NS	***	NS	NS	***	NS
5	Mean Duration of Joint "OFF" Time	NS	**	NS	NS	***	NS	NS	***	NS
6	Total Number of Joint Actuations	NS	***	NS	NS	NS	NS	NS	**	NS
7	Subtask 1 Time							NS	***	NS
8	Subtask 2 Time							NS	***	NS
9	Subtask 3 Time									
10	Subtask 1 Errors									
11	Subtask 2 Errors									
12	Subtask 3 Errors									

No.	Dependent Variables	E2 Battery Replacement								
		Left Hand			Right Hand			Both Hands		
		A	B	AxB	A	B	AxB	A	B	AxB
1	Integrated Joint Movement Time	NS	***	NS	NS	***	NS	NS	***	NS
2	Integrated Joint OFF Time	NS	NS	NS	*	***	NS	NS	***	NS
3	Time Moved: Time Not Moved Ratio	NS	**	NS	NS	***	NS	NS	***	NS
4	Mean Duration of Joint Movement Time	NS	***	NS	NS	***	NS	NS	***	NS
5	Mean Duration of Joint "OFF" Time	NS	NS	NS	**	***	*	NS	NS	NS
6	Total Number of Joint Actuations	NS	**	NS	NS	***	NS	NS	***	NS
7	Subtask 1 Time							NS	***	NS
8	Subtask 2 Time							*	***	*
9	Subtask 3 Time									
10	Subtask 1 Errors							NS	***	NS
11	Subtask 2 Errors							NS	***	NS
12	Subtask 3 Errors									

No.	Dependent Variables	E3 Compartment Inspection								
		Left Hand			Right Hand			Both Hands		
		A	B	AxB	A	B	AxB	A	B	AxB
1	Integrated Joint Movement Time	NS	***	NS	NS	***	*	NS	***	NS
2	Integrated Joint OFF Time	NS	***	NS	NS	***	*	NS	***	NS
3	Time Moved: Time Not Moved Ratio	NS	***	NS	NS	***	*	NS	***	NS
4	Mean Duration of Joint Movement Time	*	*	NS	NS	***	NS	NS	***	NS
5	Mean Duration of Joint "OFF" Time	NS	***	NS	NS	***	NS	NS	***	NS
6	Total Number of Joint Actuations	NS	***	NS	NS	**	NS	NS	**	NS
7	Subtask 1 Time							NS	***	NS
8	Subtask 2 Time							NS	***	NS
9	Subtask 3 Time							NS	***	NS
10	Subtask 1 Errors	NS	NS	NS	Not Used					
11	Subtask 2 Errors	Not Used			NS	NS	NS			
12	Subtask 3 Errors	NS	***	NS	NS	***	NS	NS	***	NS

No.	Dependent Variables	E4 Antenna Installation								
		Left Hand			Right Hand			Both Hands		
		A	B	AxB	A	B	AxB	A	B	AxB
1	Integrated Joint Movement Time				***	***	NS			
2	Integrated Joint OFF Time				***	***	NS			
3	Time Moved: Time Not Moved Ratio				NS	***	NS			
4	Mean Duration of Joint Movement Time				NS	*	NS			
5	Mean Duration of Joint "OFF" Time				NS	***	NS			
6	Total Number of Joint Actuations				***	*	NS			
7	Subtask 1 Time				*	***	NS			
8	Subtask 2 Time				***	NS	NS			
9	Subtask 3 Time									
10	Subtask 1 Errors				NS	**	NS			
11	Subtask 2 Errors				***	*	NS			
12	Subtask 3 Errors									

No.	Dependent Variables	E5 Fluid Coupling								
		Left Hand			Right Hand			Both Hands		
		A	B	AxB	A	B	AxB	A	B	AxB
1	Integrated Joint Movement Time	NS	NS	NS	NS	***	NS	NS	***	NS
2	Integrated Joint OFF Time	NS	NS	NS	NS	***	NS	NS	**	NS
3	Time Moved: Time Not Moved Ratio	NS	NS	NS	NS	***	NS	NS	***	NS
4	Mean Duration of Joint Movement Time	*	**	NS	NS	***	NS	NS	***	NS
5	Mean Duration of Joint "OFF" Time	*	*	NS	*	***	NS	*	NS	NS
6	Total Number of Joint Actuations	NS	***	NS	NS	NS	NS	NS	*	NS
7	Subtask 1 Time							*	***	NS
8	Subtask 2 Time							NS	**	NS
9	Subtask 3 Time									
10	Subtask 1 Errors	NS	NS	NS	NS	*	NS	NS	*	NS
11	Subtask 2 Errors	NS	**	NS	NS	**	NS	NS	**	NS
12	Subtask 3 Errors									

Legend
- *** Significant with $\alpha \leqslant 0.001$
- ** Significant with $\alpha \leqslant 0.01$
- * Significant with $\alpha \leqslant 0.05$
- NS Not Significant Since $\alpha > 0.05$

A = Displays
B = Controls
AxB = Control/Display Interactions

3.0 EXPERIMENT DESCRIPTIONS

This section presents, in a condensed format, the fundamental characteristics comprising each of the six experiments undertaken in this study. The objectives, experiment design, a sketch showing the configuration of the task board (work piece), a brief description of the task performed and the significant results of each experiment identified as statistically significant using analysis of variance techniques are summarized in Table V. Detailed descriptions of each experiment E1 through E6 are found in Appendix A. Equipment used in the Experiment Program are described in Appendix B.

Sufficient detail has been included in this table to provide an overview of the entire experiment program. However, two items warrant further discussion – display arrangements considered in the experiment design and the significant results.

Displays were systematically varied in the experiment design by altering the position of the camera relative to the work piece, and by varying the number of cameras used in the experiment. These variations were held constant in experiments E1, Thruster Replacement, E2, Battery Replacement, and E3, Compartment Inspection. In the conduct of the next two experiments, E4, Antenna Installation, and E5, Fluid Coupling, where the work pieces were much smaller in size, the manipulator arm completely obscured the work piece rendering the cameras which provide the side view of the work piece totally ineffective. For this reason in these two experiments the cameras were relocated to the top of the task board to yield essentially the same information to the operator but without interference from the manipulator arm. A sketch of camera positions for each manipulator experiment is shown in Figure 6.

The results entered in Table V are for each individual experiment. (Correlations of them across the experiments are made in Section 4.0 Results.) They were identified as statistically significant by the analysis of variances.

FOLDOUT FRAME 1 FOLDOUT FRAME 2

TABLE V

SUMMARY OF MANIPULATION AND MANEUVERING EXPERIMENTS

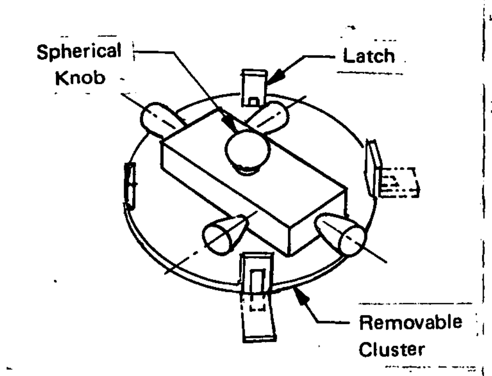
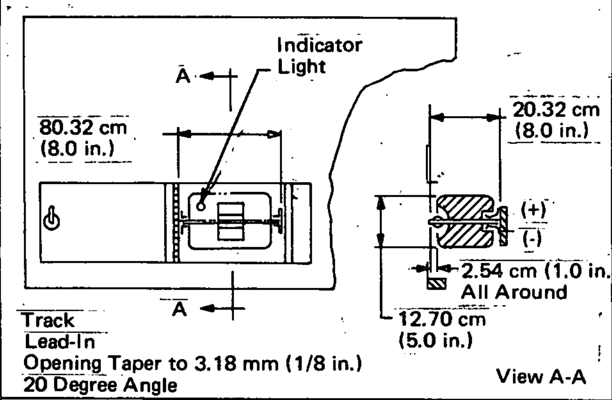
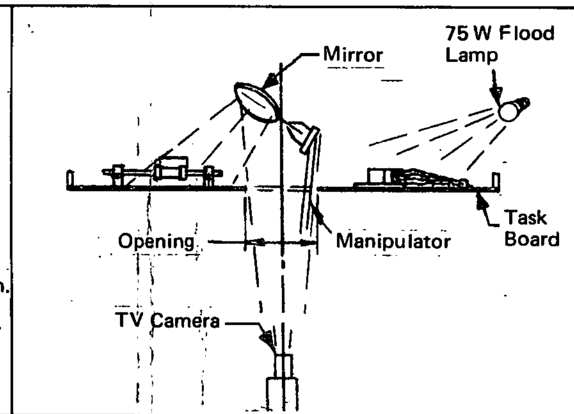
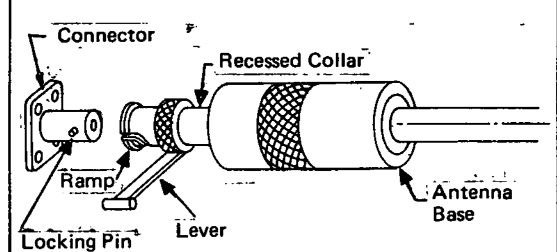
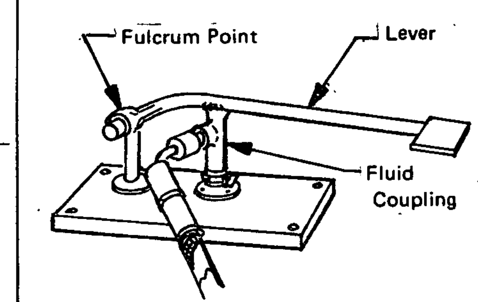
	E1 Thruster Replacement	E2 Battery Replacement	E3 Compartment Inspection	E4 Antenna Installation	E5 Fluid Coupling
1. Objective(s)	To establish the utility of a teleoperator as an operational device to maintain and service orbiting spacecraft To establish requirements for spacecraft design to permit servicing by teleoperators Specific Elements a) Engage and disengage cam-action latches b) Grasp and remove jet cluster c) Orient and engage alignment pins d) Coordination of arms in positioning and latching	To evaluate the teleoperator system in performing a typical maintenance task Specific Elements a) Engage and disengage ¼ turn latches b) Open/close hinged doors c) Extract battery from compartment d) Align flanges of battery with track e) Overcome sliding friction of electrical Connector.	To evaluate teleoperator capability in performing a routine inspection task Specific Elements a) Removal of inspection port cover b) Perform coars and fine angular motions of effector in confined spaces c) Identification of anomaly within compartment d) Replacement of port cover	Demonstrate capability to install and extend a whip antenna on a standard coaxial connector base Specific Elements a) Precise alignment of cylindrical (nesting) objects b) Force application of sufficient magnitude and proper direction to engage a standard coaxial connector	To demonstrate feasibility for orbital refueling Specific Elements a) Precise alignment of coupling elements b) Manipulation of levers to provide force amplification
2. Experiment Design	The experiment was designed to detect variation in performance of each dependent variable defined in Section 2.0, as a function of varying teleoperator system parameters. The system parameters varied (independent variables) are (A) the display arrangements used to monitor the activity at the worksite, and (B) the controllers used to remotely command and control the right and left arm of a general purpose anthropomorphic manipulator. The manipulator used in all experiments was a model 12-M manipulator designed and fabricated by Rancho Los Amigos Hospital Inc. - Three replications were made of each set of independent variables with the same subject				
A. Displays	Condition A1 - One camera normal to the task board Condition A2 - Two cameras - (1) normal and (1) at 45° to task in horizontal plane Condition A3 - Two cameras (1) normal and (1) parallel to task in the horizontal plane (orthogonal views)	Condition A1 - Same as E1 Condition A2 - Same as E1 Condition A3 - Same as E1	Condition A1 - Same as E1 Condition A2 - Same as E1 Condition A3 - Same as E1	Condition A1 - Same as E1 Condition A2 - One camera parallel to task board in the vertical plane Condition A3 - Two cameras - (1) normal and (1) parallel to task in the vertical plane (orthagonal views)	Condition A1 - Same as E1 Condition A2 - One camera normal to task board with mirror to show side view of task Condition A3 - Same as E4
B. Controllers	B1- Switch Box — Utilizing a momentary "ON" toggle switch to command motion to each joint of the manipulator arm B2- Master Controller — An exoskelton anthropomorphic controller which is "worn" by the operator - A motion on a joint of this controller will produce a corresponding motion on the slave manipulator arm B3- Lever (Joy-Stick) — Right and left lever displacements command position to the tip or jaw of the manipulator arm - Rotary joints (wrist and shoulder roll) are rate commandable from toggles on the control handle				
3. Task Board Configuration					
4. Task Description	Remove cluster assembly by opening four cam-action latches which fasten the cluster and provide compressive force to seal the propellant feed line — Replace cluster by orienting and engaging alignment pins. Close the four cam-action latches Subtask 1 - Removal Subtask 2 - Installation	Open hinged access door, retract battery pack and place it on a rack adjacent to the task board — Pick up battery align flange with track in the compartment and insert until electrical connector is engaged. Close door and lock with ¼ turn fastener Subtask 1 - Removal Subtask 2 - Installation	Gain access into a spacecraft compartment by removing an inspection port cover and inspect objects which cannot be viewed directly — Insert inspection mirror and orient it to display the reflected image of internal objects to the camera. Identify anomaly and replace port cover Subtask 1 Door Removal Subtask 2 Compartment Inspection Subtask 3 Door Replacement	Remove and reinstall a whip antenna on a standard coaxial connector base and then extend the telescoping sections of the whip to their full travel Subtask 1 - Unlock and Disengage Connector Subtask 2 - Install Antenna and Extend Whip	Engage and disengage a standard space qualified self-sealing coupling suitable for transferring fluids from one vehicle to another. Use a specially designed lever to overcome deficiency in manipulator force producing capability Subtask 1 - Engage Coupling Subtask 2 - Disengage Coupling
5. Significant Results	Experimental results depicting mean (μ) and Standard Deviation (σ) for each Statistically Significant Dependent Variable are shown in Table A. • Edge enhancement required for alignment • Flexible spherical knob desirable to relieve residual stresses in manipulator arms	Experimental results depicting mean (μ) and Standard Deviation (σ) for each Statistically Significant Dependent Variable are shown in Table B. • Manipulator did not have sufficient motion envelope to complete the task with the task board vertical - board was inclined 30° • Task was not performed with lever controller - reversal problems	Experimental results depicting mean (μ) and Standard Deviation (σ) for each Statistically Significant Dependent Variable are shown in Table C. • Difficulty was encountered in replacing port cover • Operator successfully identified all induced flaws in equipment without failure	Experimental results depicting mean (μ) and Standard Deviation (σ) for each Statistically Significant Dependent Variable are shown in Table D. • Force application combined with alignment should be avoided whenever possible • Displays relocated to overcome obscuring the work piece with manipulators	Experimental results depicting mean (μ) and Standard Deviation (σ) for each Statistically Significant Dependent Variable are shown in Table E. • Effective means of fluid transfer • Force amplification using lever proved a desirable means of augmenting manipulator capability

TABLE V

SUMMARY OF MANIPULATION AND MANEUVERING EXPERIMENTS (cont)

E6 Maneuvering and Docking

To verify capability to remotely place a teleoperator in position to perform manipulation tasks

To evaluate the effect of displays control dynamics and docking aids on maneuvering and docking accuracy and energy expenditure

Specific Elements
a) Accuracy of maneuvering and docking
b) Ability to detect a damaged cell on a solar panel
c) Evaluate stabilization system effects on TV image
d) Energy expenditure for rate versus acceleration command system

This experiment was designed to evaluate the effect of displays, flight control dynamics and docking aids on speed of performance, workload imposed by performing, energy expenditure and accuracy of performance – The equipment used were: (1) the Bell 5 DOF simulation facility consisting of the precision floor, air bearing platform, and remote maneuvering unit (RMU) with the 12-M manipulator affixed to it. All tests were conducted with the operator closing the control loop from cues derived from the single body mounted camera on the RMU. Direct viewing of the RMU or the target was not permitted. Performance was derived from data collected from three replications of tests involving each set of displays, control dynamics and docking aids.

Displays - Condition A1 - Use of a single video raster to display the image from a camera boresighted along the RMU centerline plus meter displays of range and range rate

Condition A2 - Use of a single video raster with stadia rings superimposed on the face of the display to permit stedimetric ranging - no R or $\dot{R}$ display

Control Dyn. Condition B1 - Acceleration command system for attitude stabilization

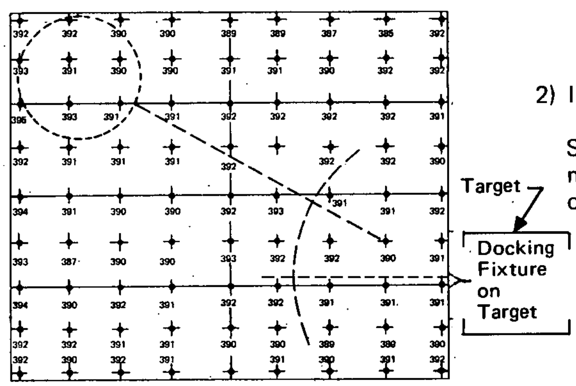
Condition B2 - Rate command system for attitude stabilization (using control moment gyros)

Docking Aids - Condition C1 - Gunsight on probe forward of RMU camera

Condition C2 - Reticle with cross hairs

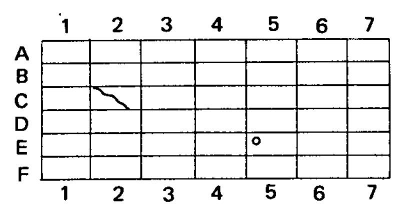
1) Maneuvering Task

Precision air bearing floor with ideal maneuver painted on the surface (see experiment E6 - Appendix A)



2) Inspection Task

Solar panel permitting relocation of damaged cells



Activate RMU systems with the RMU facing away from the target. Acquire target when RMU is within circle, translate from point (1) to point (2) at ~0.35 FPS, along the line of sight. Stop at point (2) located at 9 ft from the target. Circumnavigate target from (2) to (3) at constant range. Stop at (3) and inspect solar panel, identify row and column of damaged cells then proceed to (4) and hard dock to the target at ~0.1 to 0.2 FPS.

Experimental results depicting mean (μ) and Standard Deviation (σ) for each Statistically Significant Dependent Variable are shown in Table F.

- Electrical energy expenditure was higher with rate command
- Yawing error higher with acceleration command
- Neither control system (acceleration or rate) affect TV image
- Small structural defects (crack 1.0 in. long, 5-10 mil wide) can be detected with stand off inspection at 10 ft
- Stationkeeping accuracy to 10% of range is possible with 5 DOF

TABLE A
E1 THRUSTER REPLACEMENT

No.	Dependent Variables	Left Hand: Displays A	Left Hand: Controls B	Left Hand: Interactions AxB	Right Hand: Displays A	Right Hand: Controls B	Right Hand: Interactions AxB	Both Hands: Displays A	Both Hands: Controls B	Both Hands: Interactions AxB
1.	Integrated Joint Movement Time (min)	NS	B1 μ = 1.446 σ = 0.239 B2 μ = 2.519 σ = 0.237 B3 μ = 1.957 σ = 0.668	NS	NS	B1 μ = 1.963 σ = 0.485 B2 μ = 4.744 σ = 0.443 B3 μ = 2.923 σ = 0.820	NS	NS	B1 μ = 3.408 σ = 0.516 B2 μ = 7.263 σ = 0.634 B3 μ = 4.879 σ = 1.258	NS
2.	Integrated Joint Off Time (min)	NS	B1 μ = 17.773 σ = 1.917 B2 μ = 8.706 σ = 0.764 B3 μ = 14.108 σ = 1.700	NS	NS	B1 μ = 16.867 σ = 2.326 B2 μ = 6.499 σ = 0.572 B3 μ = 11.387 σ = 1.987	NS	NS	B1 μ = 34.874 σ = 4.046 B2 μ = 15.206 σ = 1.313 B3 μ = 25.493 σ = 3.323	NS
3.	Time Moved: Time Not Moved Ratio	NS	B1 μ = 0.082 σ = 0.014 B2 μ = 0.291 σ = 0.034 B3 μ = 0.138 σ = 0.038	NS	NS	B1 μ = 0.115 σ = 0.023 B2 μ = 0.734 σ = 0.081 B3 μ = 0.267 σ = 0.042	NS	NS	B1 μ = 0.097 σ = 0.011 B2 μ = 0.479 σ = 0.048 B3 μ = 0.190 σ = 0.039	NS
4.	Mean Duration of Joint Movement Time (sec)	NS	B1 μ = 1.662 σ = 0.244 B2 μ = 5.476 σ = 0.863 B3 μ = 2.245 σ = 1.810	NS	NS	B1 μ = 2.848 σ = 0.498 B2 μ = 7.257 σ = 1.559 B3 μ = 3.606 σ = 1.954	NS	NS	B1 μ = 2.253 σ = 0.281 B2 μ = 6.363 σ = 1.095 B3 μ = 2.924 σ = 1.831	NS
5.	Mean Duration of Joint "OFF" Time	NS	B1 μ = 31.421 σ = 4.349 B2 μ = 21.250 σ = 5.158 B3 μ = 28.419 σ = 7.376	NS	NS	B1 μ = 31.099 σ = 7.658 B2 μ = 9.434 σ = 1.312 B3 μ = 27.177 σ = 16.146	NS	NS	B1 μ = 31.257 σ = 3.547 B2 μ = 15.474 σ = 2.845 B3 μ = 27.796 σ = 10.317	NS
6.	Total Number of Joint Actuations	NS	B1 μ = 50.000 σ = 5.050 B2 μ = 29.444 σ = 3.432 B3 μ = 66.778 σ = 22.225	NS	NS	NS	NS	NS	B1 μ = 107.222 σ = 6.200 B2 μ = 75.889 σ = 8.100 B3 μ = 123.556 σ = 42.096	NS
7.	Subtask 1 Time (min)							NS	B1 μ = 1.552 σ = 0.201 B2 μ = 0.713 σ = 0.051 B3 μ = 1.153 σ = 1.170	NS
8.	Subtask 2 Time (min)							NS	B1 μ = 1.646 σ = 0.246 B2 μ = 0.891 σ = 0.093 B3 μ = 1.464 σ = 0.183	NS

Note: NS Not Significant $\alpha > 0.05$
Significance is denoted where μ, σ values are given.

TABLE B
E2 BATTERY REPLACEMENT

No.	Dependent Variables	Left Hand Displays A	Left Hand Controls B	Left Hand Interactions AxB	Right Hand Displays A	Right Hand Controls B	Right Hand Interactions AxB	Both Hands Displays A	Both Hands Controls B	Both Hands Interactions AxB
1	Integrated Joint Movement Time (min)	NS	B1 μ = 0.065 σ = 0.042 B2 μ = 0.416 σ = 0.172 B3 Abort	NS	NS	B1 μ = 2.866 σ = 0.343 B2 μ = 6.183 σ = 1.054 B3 Abort	NS	NS	B1 μ = 2.932 σ = 0.374 B2 μ = 6.600 σ = 1.194 B3 Abort	NS
2	Integrated Joint Off Time (min)	NS	NS	NS	A1 μ = 18.362 σ = 11.574 A2 μ = 15.617 σ = 9.917 A3 μ = 18.813 σ = 12.932	B1 μ = 27.950 σ = 3.537 B2 μ = 7.244 σ = 9.917 B3 Abort	NS	NS	B1 μ = 38.953 σ = 7.335 B2 μ = 17.121 σ = 5.512 B3 Abort	NS
3	Time Moved: Time Not Moved Ratio	NS	B1 μ = 0.005 σ = 0.002 B2 μ = 0.059 σ = 0.039 B3 Abort	NS	NS	B1 μ = 0.116 σ = 0.033 B2 μ = 0.868 σ = 0.205 B3 Abort	NS	NS	B1 μ = 0.076 σ = 0.008 B2 μ = 0.444 σ = 0.116 B3 Abort	NS
4	Mean Duration of Joint Movement Time (sec)	NS	B1 μ = 0.147 σ = 0.065 B2 μ = 1.007 σ = 0.406 B3 Abort	NS	NS	B1 μ = 1.220 σ = 0.139 B2 μ = 2.602 σ = 0.906 B3 Abort	NS	NS	B1 μ = 0.727 σ = 0.152 B2 μ = 1.804 σ = 0.580 B3 Abort	NS
5	Mean Duration of Joint "OFF" Time (sec)	NS	NS	NS	A1 μ = 8.186 σ = 5.673 A2 μ = 6.998 σ = 4.396 A3 μ = 8.835 σ = 6.264	B1 μ = 12.936 σ = 1.770 B2 μ = 3.077 σ = 0.461 B3 Abort	*	NS	NS	NS
6	Total Number of Joint Actuations	NS	B1 μ = 8.111 σ = 4.197 B2 μ = 16.444 σ = 4.746 B3 Abort	NS	NS	B1 μ = 236.111 σ = 22.127 B2 μ = 169.000 σ = 35.944 B3 Abort	NS	NS	B1 μ = 244.222 σ = 22.432 B2 μ = 185.444 σ = 32.527 B3 Abort	NS
7.	Subtask 1 Time (min)							NS	B1 μ = 2.412 σ = 0.238 B2 μ = 0.918 σ = 0.081 B3 Abort	NS
8	Subtask 2 Time (min)							A1 μ = 1.976 σ = 1.156 A2 μ = 1.594 σ = 0.661 A3 μ = 2.052 σ = 1.095	B1 μ = 2.730 σ = 0.528 B2 μ = 1.019 σ = 0.148 B3 Abort	*
9	Subtask 3 Time									
10	Subtask 1 Errors							NS	B1 μ = 5.667 σ = 2.398 B2 μ = 1.333 σ = 0.866 B3 Abort	NS
11	Subtask 2 Errors							NS	B1 μ = 8.889 σ = 2.759 B2 μ = 2.222 σ = 1.481 B3 Abort	NS
12	Subtask 3 Errors									

Note:
* Significant with $\alpha \leqslant 0.05$
NS Not Significant $\alpha > 0.05$
Abort = Inability to perform test. In this experiment the aborts were caused by continually recurring control reversals.
Significance is denoted where μ, σ values are given.

TABLE C
E3 COMPARTMENT INSPECTION

No.	Dependent Variables	Left Hand			Right Hand			Both Hands		
		Displays A	Controls B	Interactions A x B	Displays A	Controls B	Interactions A x B	Displays A	Controls B	Interactions A x B
1	Integrated Joint Movement Time (sec)	NS	B1 μ = 58.472, σ = 7.608 B2 μ = 99.011, σ = 8.026 B3 μ = 78.967, σ = 10.652	NS	NS	B1 μ = 30.644, σ = 5.346 B2 μ = 52.511, σ = 7.374 B3 μ = 54.455, σ = 8.509	*	NS	B1 μ = 89.117, σ = 6.560 B2 μ = 151.522, σ = 10.967 B3 μ = 133.422, σ = 15.917	NS
2	Integrated Joint OFF Time (sec)	NS	B1 μ = 958.032, σ = 147.568 B2 μ = 334.989, σ = 45.063 B3 μ = 577.033, σ = 71.699	NS	NS	B1 μ = 797.288, σ = 142.128 B2 μ = 312.922, σ = 47.945 B3 μ = 468.989, σ = 80.826	*	NS	B1 μ = 1754.098, σ = 282.631 B2 μ = 647.922, σ = 90.383 B3 μ = 1046.021, σ = 143.701	NS
3	Time Moved: Time Not Moved Ratio	NS	B1 μ = 0.062, σ = 0.008 B2 μ = 0.299, σ = 0.039 B3 μ = 0.139, σ = 0.029	NS	NS	B1 μ = 0.040, σ = 0.010 B2 μ = 0.171, σ = 0.035 μ = 0.121, σ = 0.038	*	NS	B1 μ = 0.052, σ = 0.007 B2 μ = 0.237, σ = 0.030 B3 μ = 0.131, σ = 0.029	NS
4	Mean Duration of Joint Movement Time (sec)	A1 μ = 1.174, σ = 1.477 A2 μ = 1.721, σ = 0.575 A3 μ = 1.389, σ = 0.340	B1 μ = 1.319, σ = 1.317 B2 μ = 1.744, σ = 0.709 B3 μ = 1.222, σ = 0.260	NS	NS	B1 μ = 0.941, σ = 0.488 B2 μ = 1.783, σ = 0.307 B3 μ = 1.605, σ = 0.363	NS	NS	B1 μ = 1.130, σ = 0.341 B2 μ = 1.763, σ = 0.253 B3 μ = 1.413, σ = 0.167	NS
5	Mean Duration of Joint "OFF" Time (sec)	NS	B1 μ = 20.538, σ = 5.265 B2 μ = 8.304, σ = 2.716 B3 μ = 21.437, σ = 7.171	NS	NS	B1 μ = 28.220, σ = 8.264 B2 μ = 12.932, σ = 4.477 B3 μ = 22.479, σ = 7.395	NS	NS	B1 μ = 24.379, σ = 5.637 B2 μ = 10.618, σ = 3.329 B3 μ = 21.958, σ = 4.375	NS
6	Total Number of Joint Actuations	NS	B1 μ = 109.000, σ = 19.647 B2 μ = 56.778, σ = 8.167 B3 μ = 65.667, σ = 10.380	NS	NS	B1 μ = 33.333, σ = 5.545 B2 μ = 28.111, σ = 6.698 B3 μ = 23.556, σ = 4.362	NS	NS	B1 μ = 142.333, σ = 20.815 B2 μ = 84.889, σ = 10.982 B3 μ = 89.222, σ = 9.985	NS
7	Subtask 1 Time (sec)							NS	B1 μ = 51.333, σ = 5.074 B2 μ = 21.000, σ = 4.153 B3 μ = 36.000, σ = 7.953	NS
8	Subtask 2 Time (sec)							NS	B1 μ = 20.056, σ = 4.978 B2 μ = 13.778, σ = 4.177 B3 μ = 17.556, σ = 5.548	NS
9	Subtask 3 Time (sec)							NS	B1 μ = 97.889, σ = 23.079 B2 μ = 27.111, σ = 3.551 B3 μ = 54.556, σ = 10.806	NS
10	Subtask 1 Errors	NS	NS	NS	NOT USED					
11	Subtask 2 Errors	NOT USED			NS	NS	NS			
12	Subtask 3 Errors	NS	B1 μ = 5.444, σ = 2.698 B2 μ = 0.778, σ = 0.667 B3 μ = 1.556, σ = 1.130	NS	NS	B1 μ = 1.667, σ = 1.000 B2 μ = 0.111, σ = 0.333 B3 μ = 0.556, σ = 0.726	NS	NS	B1 μ = 10.444, σ = 2.555 B2 μ = 2.667, σ = 1.658 B3 μ = 4.889, σ = 2.028	NS

Note:
* Significant with $\alpha \leqslant 0.05$

NS Not Significant $\alpha > 0.05$

Significance is denoted where μ, σ values are given.

TABLE D
E4 ANTENNA INSTALLATION

No.	Dependent Variables	Right Hand: Displays A	Right Hand: Controls B	Right Hand: Interactions AxB
1.	Integrated Joint Movement Time (sec)	A1 μ = 195.467 σ = 67.345 A2 μ = 312.189 σ = 158.849 A3 μ = 189.022 σ = 76.74	B1 μ = 122.178 σ = 26.041 B2 μ = 326.055 σ = 120.841 B3 μ = 248.444 σ = 85.822	NS
2.	Integrated Joint Off Time (sec)	A1 μ = 672.088 σ = 299.071 A2 μ =1038.032 σ = 496.796 A3 μ = 650.199 σ = 301.735	B1 μ =1219.821 σ = 348.427 B2 μ = 525.611 σ = 187.154 B3 μ = 614.887 σ = 238.178	NS
3.	Time Moved: Time Not Moved Ratio	NS	B1 μ = 0.102 σ = 0.013 B2 μ = 0.625 σ = 0.095 B3 μ = 0.414 σ = 0.057	NS
4.	Mean Duration of Joint Movement	NS	B1 μ = 1.731 σ = 0.343 B2 μ = 2.195 σ = 0.324 B3 μ = 1.973 σ = 0.171	NS
5.	Mean Duration of Joint "Off" Time (sec)	NS	B1 μ = 17.542 σ = 7.446 B2 μ = 4.341 σ = 1.140 B3 μ = 15.760 σ = 6.661	NS
6.	Total Number of Joint Actuations	A1 μ = 143.222 σ = 32.326 A2 μ = 212.667 σ = 63.644 A3 μ = 126.444 σ = 29.971	B1 μ = 177.778 σ = 49.472 B2 μ = 172.556 σ = 61.648 B3 μ = 132.000 σ = 55.089	NS
7.	Subtask 1 Time (sec)	A1 μ = 72.000 σ = 30.430 A2 μ = 85.556 σ = 37.839 A3 μ = 73.556 σ = 28.245	B1 μ = 117.667 σ = 17.727 B2 μ = 55.333 σ = 10.954 B3 μ = 58.111 σ = 7.424	NS
8.	Subtask 2 Time (sec)	A1 μ = 67.667 σ = 33.283 A2 μ = 129.889 σ = 50.429 A3 μ = 60.667 σ = 20.100	NS	NS
9.	Subtask 3 Time			
10.	Subtask 1 Errors	NS	B1 μ = 7.444 σ = 4.216 B2 μ = 5.222 σ = 1.716 B3 μ = 3.444 σ = 2.007	NS
11.	Subtask 2 Errors	A1 μ = 7.773 σ = 5.142 A2 μ = 18.111 σ = 11.505 A3 μ = 4.444 σ = 1.810	B1 μ = 15.111 σ = 12.850 B2 μ = 6.222 σ = 4.790 B3 μ = 9.000 σ = 6.461	NS

Note: NS Not Significant $\alpha > 0.05$
Significance is denoted where μ, σ values are given.

TABLE E
E5 FLUID COUPLING

No.	Dependent Variables	Left Hand Displays A	Left Hand Controls B	Left Hand Interact AxB	Right Hand Displays A	Right Hand Controls B	Right Hand Interact AxB	Both Hands Displays A	Both Hands Controls B	Both Hands Interact AxB
1.	Integrated Joint Movement Time (sec)	NS	NS	NS	NS	B1 μ = 51.800 σ = 13.620 B2 μ = 125.133 σ = 13.369 B3 μ = 137.855 σ = 37.530	NS	NS	B1 μ = 89.433 σ = 20.271 B2 μ = 172.789 σ = 21.382 B3 μ = 177.644 σ = 38.817	NS
2.	Integrated Joint Off Time (sec)	NS	NS	NS	NS	B1 μ = 500.088 σ = 89.357 B2 μ = 230.867 σ = 34.505 B3 μ = 377.144 σ = 91.395	NS	NS	B1 μ = 783.566 σ = 156.084 B2 μ = 503.766 σ = 73.894 B3 μ = 646.77 σ = 162.090	NS
3.	Time Moved: Time Not Moved Ratio	NS	NS	NS	NS	B1 μ = 0.105 σ = 0.024 B2 μ = 0.545 σ = 0.035 B3 μ = 0.369 σ = 0.063	NS	NS	B1 μ = 0.116 σ = 0.024 B2 μ = 0.346 σ = 0.048 B3 μ = 0.278 σ = 0.029	NS
4.	Mean Duration of Joint Movement Time (sec)	A1 μ = 1.146 σ = 0.922 A2 μ = 0.550 σ = 0.247 A3 μ = 0.629 σ = 0.361	B1 μ = 0.254 σ = 0.059 B2 μ = 1.026 σ = 0.320 B3 μ = 1.045 σ = 0.844	NS	NS	B1 μ = 0.742 σ = 0.538 B2 μ = 1.591 σ = 0.116 B3 μ = 1.150 σ = 0.267	NS	NS	B1 μ = 0.548 σ = 0.299 B2 μ = 1.308 σ = 0.160 B3 μ = 1.098 σ = 0.396	NS
5.	Mean Duration of Joint "OFF" Time (sec)	A1 μ = 9.178 σ = 3.851 A2 μ = 5.327 σ = 2.235 A3 μ = 9.126 σ = 4.456	B1 μ = 6.895 σ = 2.716 B2 μ = 10.366 σ = 4.012 B3 μ = 6.104 σ = 3.851	NS	A1 μ = 4.985 σ = 2.067 A2 μ = 4.686 σ = 2.115 A3 μ = 6.267 σ = 2.154	B1 μ = 7.475 σ = 1.930 B2 μ = 3.480 σ = 1.057 B3 μ = 4.984 σ = 0.984	NS	A1 μ = 7.082 σ = 1.966 A2 μ = 5.007 σ = 1.489 A3 μ = 7.696 σ = 1.933	NS	NS
6.	Total Number of Joint Actuations	NS	B1 μ = 60.667 σ = 31.361 B2 μ = 37.222 σ = 9;458 B3 μ = 24.667 σ = 9.097	NS	NS	NS	NS	NS	B1 μ = 133.111 σ = 42.230 B2 μ = 105.222 σ = 15.246 B3 μ = 102.889 σ = 19.580	NS
7.	Subtask 1 Time (sec)							A1 μ = 49.556 σ = 17.422 A2 μ = 44.222 σ = 9.271 A3 μ = 55.444 σ = 13.848	B1 μ = 63.000 σ = 11.630 B2 μ = 35.778 σ = 6.180 B3 μ = 50.444 σ = 7.812	NS
8.	Subtask 2 Time (sec)							NS	B1 μ = 47.111 σ = 9.662 B2 μ = 23.556 σ = 3.844 B3 μ = 52.556 σ = 24.511	NS
9.	Subtask 3 Time									
10.	Subtask 1 Errors	NS	NS	NS	NS	B1 μ = 2.333 σ = 1.323 B2 μ = 1.000 σ = 0.707 B3 μ = 1.667 σ = 0.866	NS	NS	B1 μ = 4.889 σ = 1.833 B2 μ = 2.222 σ = 1.641 B3 μ = 4.111 σ = 1.691	NS
11.	Subtask 2 Errors	NS	B1 μ = 0.333 σ = 0.707 B2 μ = 1.111 σ = 0.782 B3 μ = 1.667 σ = 0.866	NS	NS	B1 μ = 4.222 σ = 1.394 B2 μ = 2.444 σ = 1.424 B3 μ = 11.222 σ = 8.212	NS	NS	B1 μ = 4.556 σ = 1.740 B2 μ = 3.556 σ = 1.130 B3 μ = 12.889 σ = 8.388	NS
12.	Subtask 3 Errors									

Note: NS Not Significant $\alpha > 0.05$
Significance is denoted where μ, σ values are given.

TABLE F
E6 MANEUVERING AND DOCKING

	Energy Expenditure: Fuel % Used	Energy Expenditure: Battery % Used	Translation: ($\dot{R}$) ft/sec	$\dot{R}_{peak}$ ft/sec	(ϵ_p) (Deg)	(ϵ_y) (Deg)	(ϵ_r) (Deg)	(Y) (ft)	Total Time
A	NS	NS	NS	NS	NS	NS	NS	NS	NS
B	NS	B1 μ 6.000 σ 1.128 B2 μ 10.000 σ 3.618	NS	NS	NS	B1 μ 3.033 σ 1.154 B2 μ 0.825 σ 0.622	NS	NS	NS
C	NS	NS	NS	NS	NS	NS	NS	NS	NS
A x B	NS	NS	NS	NS	*	NS	*	NS	NS
A x C	NS	NS	NS	NS	NS	NS	NS	NS	NS
B x C	NS	NS	NS	NS	NS	NS	NS	NS	NS
A x B x C	NS	NS	NS	NS	NS	NS	*	NS	NS

	E_{Range}: Circ ft	E_{Range}: Insp ft	Docking (Instantaneous): $\dot{R}$ ft/sec	(ϵ_p) Deg	(ϵ_y) Deg	(ϵ_r) Deg	(y)	Total Time
A	NS	NS	NS	NS	NS	NS	NS	NS
B	NS	NS	B1 μ 0.222 σ 0.035 B2 μ 0.280 σ 0.072	NS	NS	NS	B1 μ 1.083 σ 0.790 B2 μ 0.417 σ 0.790	NS
C	NS	NS	B1 μ 0.230 σ 0.043 B2 μ 0.272 σ 0.073	NS	NS	NS	NS	NS
A x B	NS	NS	NS	NS	NS	NS	NS	NS
A x C	NS	NS	NS	NS	NS	NS	*	NS
B x C	NS	NS	NS	NS	NS	NS	NS	NS
A x B x C	NS	NS	*	NS	NS	*	NS	NS

CODE:

NS = Not Significant
* = $\alpha \leqslant 0.05$
A = Displays
B = Controls
C = Docking Aids

Significance is denoted where
μ, σ values are given

DISPLAY ARRANGEMENTS

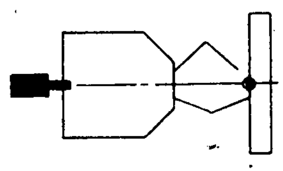
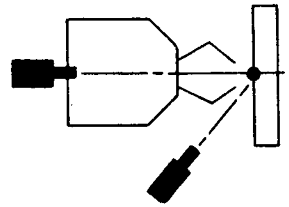
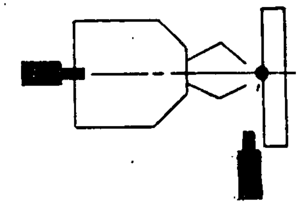
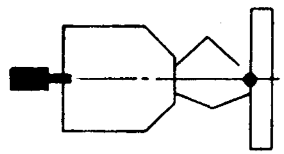
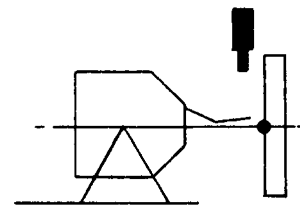
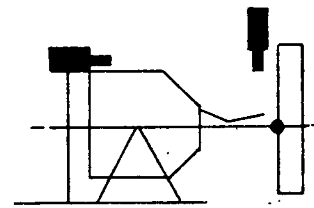
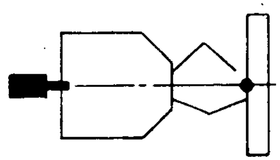
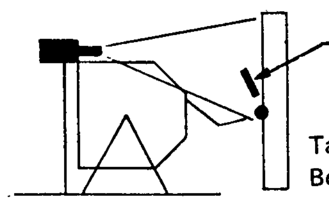
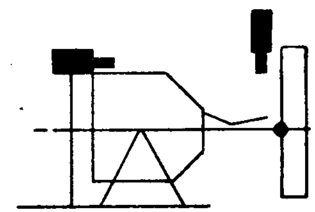
Experiment	Condition A1	Condition A2	Condition A3
E1 - Thruster Replacement E2 - Battery Replacement E3 - Compartment Inspection	 Task Board 1 Camera - Normal	 Task Board 2 Cameras – 1 Normal, 1 at 45° Horizontal	 Task Board 2 Cameras – 1 Normal, 1 Parallel Horizontal
E4 - Antenna Installation	 Task Board 1 Camera - Normal	 Task Board 1 Camera - Vertical	 Task Board 2 Cameras – 1 Normal, 1 Parallel Vertical
E5 - Fluid Coupling	 Task Board 1 Camera - Normal	 Mirror at 45° Task Board 1 Camera - Normal with Mirror	 Task Board 2 Cameras – 1 Normal, 1 Parallel Vertical

Figure 6. Camera Arrangements

4.0 EXPERIMENT ANALYSES

4.1 MANIPULATION EXPERIMENTS E1 THROUGH E5

4.1.1 Significance of Displays (A)

The evaluated display configurations are indicated in Table VI. Each was employed with each of the three controllers for three replications of the experiment as previously indicated in Table III. Results of the analysis of variances are presented in Table VII under the columns labeled "A." These confirm that the performance of the teleoperator systems is relatively insensitive to the variations in displays, because a suitably designed work piece is used in the experiment.

A suitably designed work piece is one which incorporates features that yield additional cues – edge enhancement was one extensively used technique which aided depth perception; markings to assist orientation between parts was another.

The following are considerations of each dependent variable:

1. Integrated Joint Movement Time

This parameter was computed by summing the times during which there was actual movement in each individual joint of the actuator arms. It is thus a measure of total system activity. Being the total power put into the system it may be related to physical workload. Examination of the first row of Table VII shows that no significant change in this parameter was attributable to variation in displays with the exception of E4, Antenna Installation. Table VI shows that this was the only experiment conducted where a camera normal to the task board was not present in all evaluated display combinations. Moreover, as noted in Table VI, it proved impossible to complete the experiment without such a camera.

Thus, it may be concluded that a single camera appears to provide a significant portion of the information required for minimizing system activity during task completion. While additional cameras do improve performance, this increment is not sufficient to be statistically significant.

This rather startling result is shown graphically in Figure 7 where Integrated Joint Movement time data from E4, Antenna Installation, is shown as a function of displays. Mean, range and standard deviation are depicted. It can be seen that there is no difference in this parameter between A_1 (single normal camera) and A_3 (2 cameras, one normal and one parallel in the vertical plane). The addition of the second camera in condition A_3 might be thought to give additional depth cues; however, the data show that if this is so, the additions were unnecessary insofaras minimizing total system activity is concerned. For this particular task, the A_2 condition (single camera, parallel to the task board in the vertical axis) requires significantly more system activity and produces greater variation in performance. This is because the information gained from this camera is insufficient to overcome the loss of information from the camera located normal to the task board. Also, to some extent, the depth cues provided under A_2, (the camera parallel to the task board) are not missed under A_1 (the single normal camera) due to the design of the task board. Placing the antenna against the alignment guide, gives automatic positioning. (See Figure 7a.)

TABLE VI
SUMMARY OF THE DISPLAY CONFIGURATIONS EVALUATED

	Displays		
Experiment	A_1	A_2	A_3
E1 Thruster Replacement	1 Camera Normal to Task Board	2 Cameras 1 Normal and 1 at 45° to Task in Horizontal Plane	2 Cameras 1 Normal and 1 Parallel to Task in Horizontal Plane
E2 Battery Replacement		Same as above	Same as above
E3 Compartment Inspection		Same as above	Same as above
E4 Antenna Installation		1 Camera Parallel to Task Board in Vertical Plane	2 Cameras 1 Normal and 1 Parallel Task in Vertical Plane
E5 Fluid Coupling		*1 Camera Normal to Task Board with Mirror	2 Cameras 1 Normal and 1 Parallel Task in Vertical Plane

*Note: A single camera mounted parallel and vertically above the taskboard for. Experiment E4 proved inadequate, task completion being impossible. The condition was therefore replaced with the mirror arrangement

FOLDOUT FRAME 1

FOLDOUT FRAME 2

TABLE VII
RESULTS OF ANALYSIS OF VARIANCE
MANIPULATION EXPERIMENTS E1 THROUGH E5

E1 Thruster Replacement

No.	Dependent Variables	Left Hand A	Left Hand B	Left Hand AxB	Right Hand A	Right Hand B	Right Hand AxB	Both Hands A	Both Hands B	Both Hands AxB
1	Integrated Joint Movement Time	NS	***	NS	NS	***	NS	NS	***	NS
2	Integrated Joint OFF Time	NS	***	NS	NS	***	NS	NS	***	NS
3	Time Moved: Time Not Moved Ratio	NS	***	NS	NS	***	NS	NS	***	NS
4	Mean Duration of Joint Movement Time	NS	***	NS	NS	***	NS	NS	***	NS
5	Mean Duration of Joint "OFF" Time	NS	**	NS	NS	***	NS	NS	***	NS
6	Total Number of Joint Actuations	NS	***	NS	NS	NS	NS	NS	**	NS
7	Subtask 1 Time							NS	***	NS
8	Subtask 2 Time							NS	***	NS
9	Subtask 3 Time									
10	Subtask 1 Errors									
11	Subtask 2 Errors									
12	Subtask 3 Errors									

E2 Battery Replacement

No.	Dependent Variables	Left Hand A	Left Hand B	Left Hand AxB	Right Hand A	Right Hand B	Right Hand AxB	Both Hands A	Both Hands B	Both Hands AxB
1	Integrated Joint Movement Time	NS	***	NS	NS	***	NS	NS	***	NS
2	Integrated Joint OFF Time	NS	NS	NS	*	***	NS	NS	***	NS
3	Time Moved: Time Not Moved Ratio	NS	**	NS	NS	***	NS	NS	***	NS
4	Mean Duration of Joint Movement Time	NS	***	NS	NS	***	NS	NS	***	NS
5	Mean Duration of Joint "OFF" Time	NS	NS	NS	**	***	*	NS	NS	NS
6	Total Number of Joint Actuations	NS	**	NS	NS	***	NS	NS	***	NS
7	Subtask 1 Time							NS	***	NS
8	Subtask 2 Time							*	***	*
9	Subtask 3 Time									
10	Subtask 1 Errors							NS	***	NS
11	Subtask 2 Errors							NS	***	NS
12	Subtask 3 Errors									

E3 Compartment Inspection

No.	Dependent Variables	Left Hand A	Left Hand B	Left Hand AxB	Right Hand A	Right Hand B	Right Hand AxB	Both Hands A	Both Hands B	Both Hands AxB
1	Integrated Joint Movement Time	NS	***	NS	NS	***	*	NS	***	NS
2	Integrated Joint OFF Time	NS	***	NS	NS	***	*	NS	***	NS
3	Time Moved: Time Not Moved Ratio	NS	***	NS	NS	***	*	NS	***	NS
4	Mean Duration of Joint Movement Time	*	*	NS	NS	***	NS	NS	***	NS
5	Mean Duration of Joint "OFF" Time	NS	***	NS	NS	***	NS	NS	***	NS
6	Total Number of Joint Actuations	NS	***	NS	NS	**	NS	NS	**	NS
7	Subtask 1 Time							NS	***	NS
8	Subtask 2 Time							NS	***	NS
9	Subtask 3 Time							NS	***	NS
10	Subtask 1 Errors	NS	NS	NS	Not Used					
11	Subtask 2 Errors	Not Used			NS	NS	NS			
12	Subtask 3 Errors	NS	***	NS	NS	***	NS	NS	***	NS

E4 Antenna Installation

No.	Dependent Variables	Left Hand A	Left Hand B	Left Hand AxB	Right Hand A	Right Hand B	Right Hand AxB	Both Hands A	Both Hands B	Both Hands AxB
1	Integrated Joint Movement Time				***	***	NS			
2	Integrated Joint OFF Time				***	***	NS			
3	Time Moved: Time Not Moved Ratio				NS	***	NS			
4	Mean Duration of Joint Movement Time				NS	*	NS			
5	Mean Duration of Joint "OFF" Time				NS	***	NS			
6	Total Number of Joint Actuations				***	*	NS			
7	Subtask 1 Time				*	***	NS			
8	Subtask 2 Time				***	NS	NS			
9	Subtask 3 Time									
10	Subtask 1 Errors				NS	**	NS			
11	Subtask 2 Errors				***	*	NS			
12	Subtask 3 Errors									

E5 Fluid Coupling

No.	Dependent Variables	Left Hand A	Left Hand B	Left Hand AxB	Right Hand A	Right Hand B	Right Hand AxB	Both Hands A	Both Hands B	Both Hands AxB
1	Integrated Joint Movement Time	NS	NS	NS	NS	***	NS	NS	***	NS
2	Integrated Joint OFF Time	NS	NS	NS	NS	***	NS	NS	**	NS
3	Time Moved: Time Not Moved Ratio	NS	NS	NS	NS	***	NS	NS	***	NS
4	Mean Duration of Joint Movement Time	*	**	NS	NS	***	NS	NS	***	NS
5	Mean Duration of Joint "OFF" Time	*	*	NS	*	***	NS	*	NS	NS
6	Total Number of Joint Actuations	NS	***	NS	NS	NS	NS	NS	*	NS
7	Subtask 1 Time							*	***	NS
8	Subtask 2 Time							NS	**	NS
9	Subtask 3 Time									
10	Subtask 1 Errors	NS	NS	NS	NS	*	NS	NS	*	NS
11	Subtask 2 Errors	NS	**	NS	NS	**	NS	NS	**	NS
12	Subtask 3 Errors									

Legend

*** Significant with $\alpha \leq 0.001$
** Significant with $\alpha \leq 0.01$
* Significant with $\alpha \leq 0.05$
NS Not Significant Since $\alpha > 0.05$

A = Displays
B = Controls
AxB = Control/Display Interactions

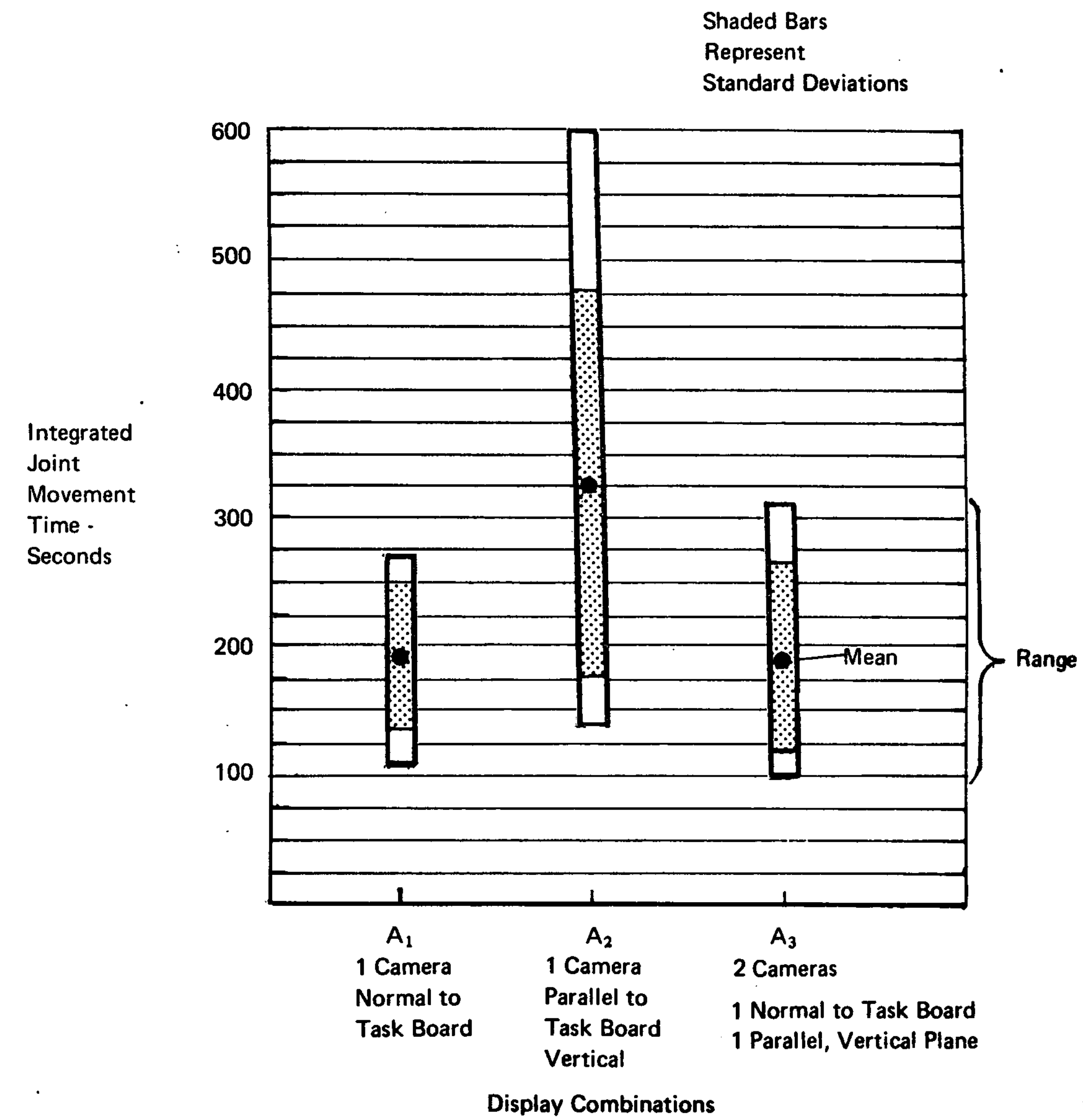


Figure 7. A Selected Result E4 Antenna Installation

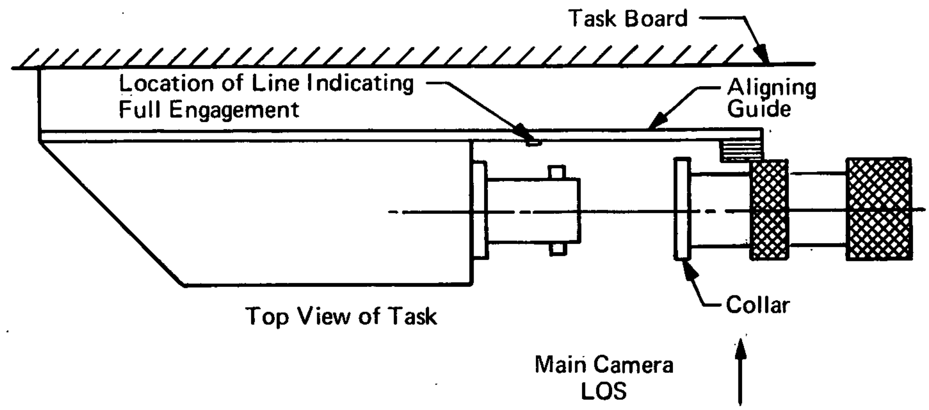


Figure 7a. Alignment Guide for E-4 Antenna Installation

2. Integrated Joint OFF Time

This parameter was computed by summing the times during which each joint was at rest during the performance of the task. It is thus a measure of total system inactivity and was chosen for its relationship with mental workload. It was postulated that as the requirements for total thinking time increased, due to increased task difficulty, the Integrated Joint OFF Time would also increase.

As may be seen in Table VII the results for this parameter are similar to those for Integrated Joint Movement time, and may be explained using similar arguments. However, it may be noted that there is an additional significant effect for displays in E2 Battery Replacement. The nature of this relationship is plotted in Figure 8 where it can be seen that there is no significant difference between A_1 (single normal camera) and A_3 (2 cameras, one normal and one parallel in the horizontal plane); however, A_2 (2 cameras, one normal and one at 45° in the horizontal plane) minimizes the mental workload. This is due to the special nature of the task. Replacing the battery pack in the interior compartment, called for a difficult alignment maneuver. Only a camera mounted at 45° gave a good view of this. The conclusions are that a single normal camera is by far the most important source of display information and that additional cameras often fail to yield significant improvement in performance. But, in certain special situations such as those encountered in E2 Battery Replacement and E4 Antenna Installation, a second appropriately located camera can help. Please note that no task ever proved too difficult to complete provided a view through a camera normal to the task board was available.

3. Time Moved/Time Not Moved Ratio

This parameter was computed directly from the preceding two. In no instance did it show a significant variation as a function of display changes, and, as will be brought out later in a discussion of the correlation data, should probably be eliminated from future research.

4. Mean Duration of Joint Movement Time

This parameter was computed by dividing the Integrated Joint Movement Time by the total number of actuations made by all the joints during the trial. In only two instances was an effect attributable to displays, i.e., E3, Compartment Inspection, and E5, Fluid Coupling. The comparative nature of these two relationships for the left hand is shown in Figure 9.

Note that A_1 (single normal camera) was the only display condition identical between the two experiments, and that Mean Duration of Joint Movement time, is the same for both experiments. The means for the other display combinations are different because of the differences in the displays.

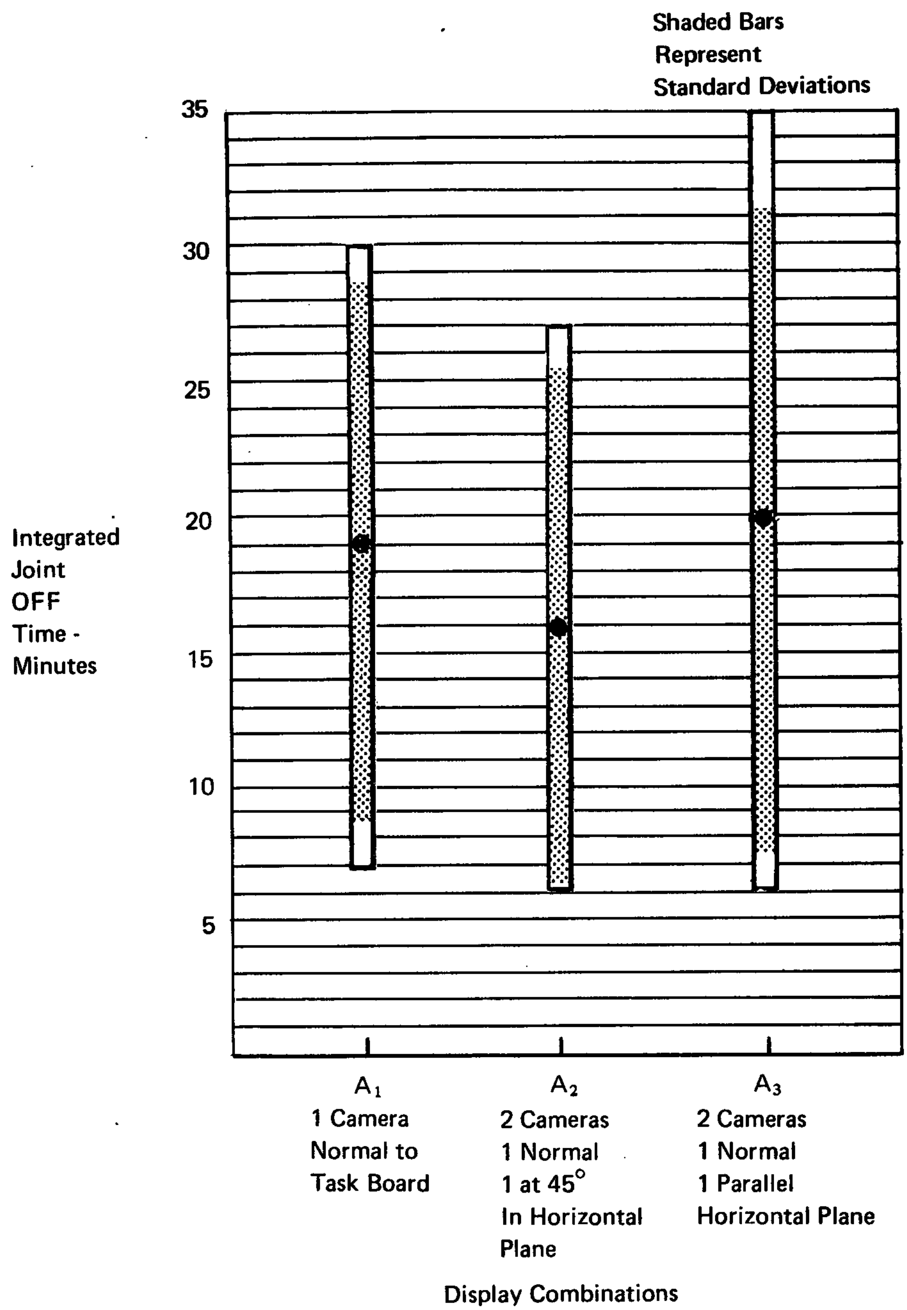


Figure 8. A Selected Result of E2 Battery Replacement

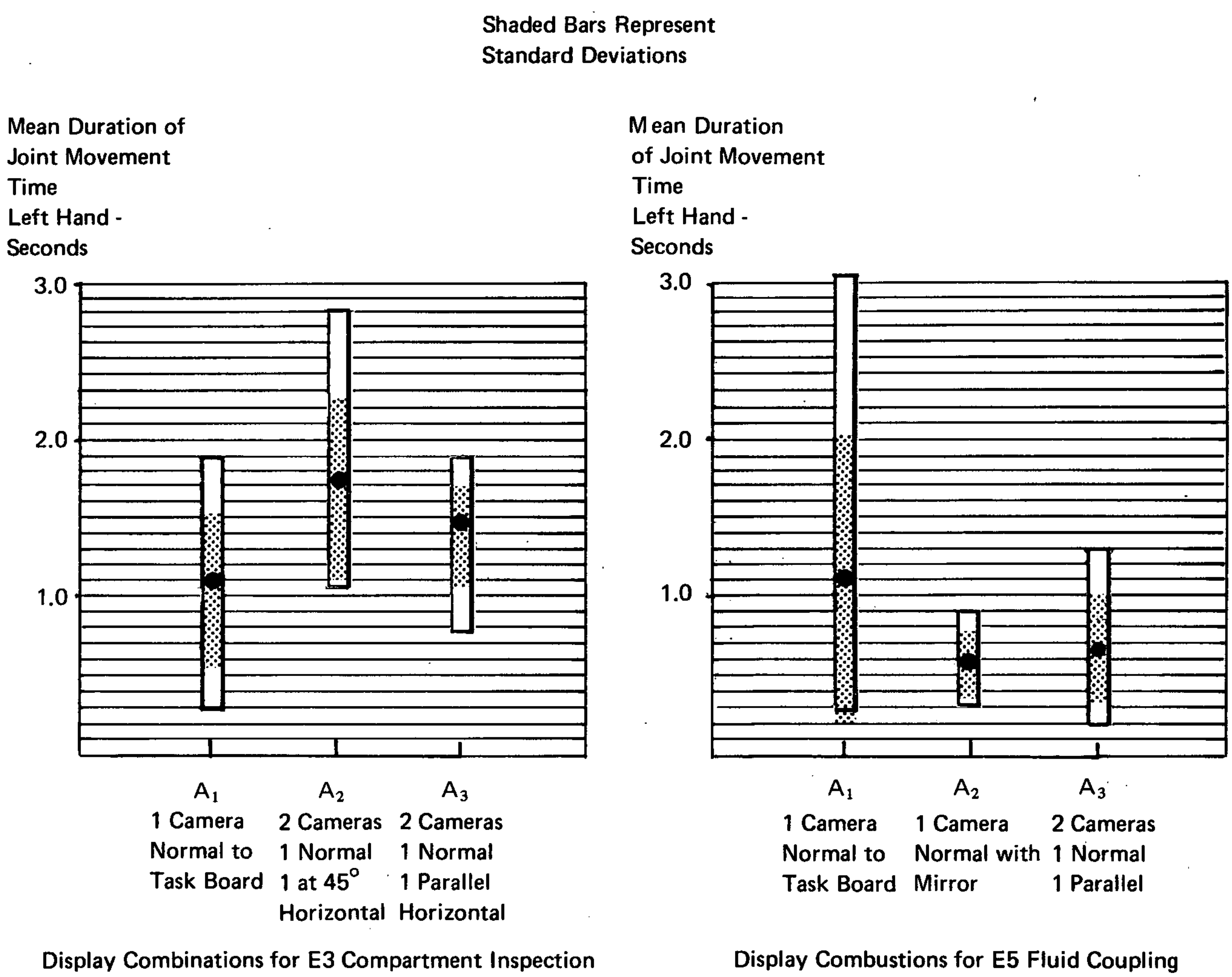


Figure 9. Comparison of the Effects of Displays in E3 Compartment Inspection and E5 Fluid Coupling

The A_2 combination in experiment E5 is of particular importance. It consists of a single normal camera and a mirror placed above the work piece as shown in Figure 10. The mirror is inclined 45° so that the reflected image of the top view of the work piece can be seen with the main camera. This information, usually provided by an auxiliary camera, is gained here without the cost and complexity associated with a secondary TV system.

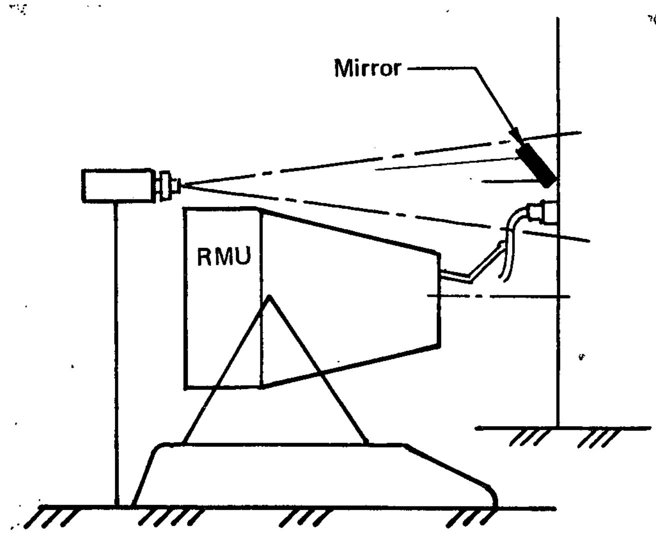


Figure 10. Mirror Installation

Using a mirror as a substitute for the auxiliary camera yields the following advantages:

a. Combines both normal and orthogonal views of the workpiece into a single display raster, eliminating the need for the operator to scan the displays.

b. In an operational teleoperator, elimination of the second TV reduces the bandwidth required for video transmission by approximately 4.6 MHz, and concurrently simplifies the system.

c. It provides the most needed information because it is placed in position by the manipulator at initiation of the task.

d. Requires an additional manipulator arm task (to place the mirror).

5. Mean Duration of Joint OFF Time

This parameter was computed by dividing the Integrated Joint OFF Time by the total number of actuations made by all joints during a trial. This quotient is related to mental workload since its values increase as requirements for thinking time increase.

A significant variation was noted for two experiments: E2, Battery Replacement, and E5, Fluid Coupling. In the case of E2 a significant interaction was also noted between the effects of displays and those of controls. The results for E2 are summarized graphically in Figure 11. These effects occurred only for the right-hand manipulator; no significant effects were noted for the left. Left-hand activity was not only a small portion of the total, but essentially simple in nature; whereas right-hand activity was much more exacting and therefore much more likely to respond to changes in displays and controls.

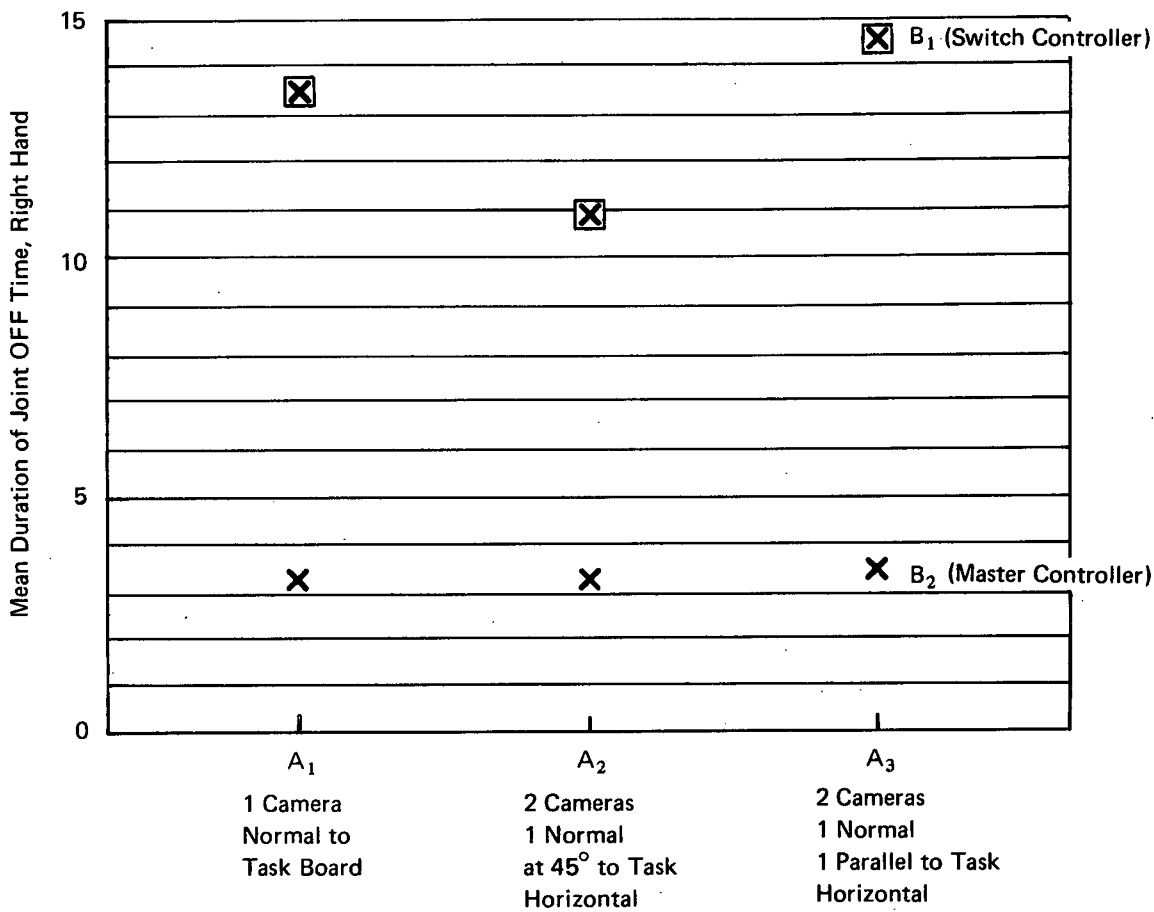


Figure 11. E2 Battery Replacement Data Depicting Significant Difference Across A (Displays) As Related to Interactive Effects With Control

It is clear from Figure 11 that the significant difference along dimension A (displays) comes almost entirely from use of a switchbox as a controller. Very little difference occurs across displays using the Master Controller. This accounts for the significant interaction between controls and displays and may be interpreted as meaning that the importance of displays, at least in some special situations such as E2, Battery Replacement, depends upon the type of control system used. Thus the effect of the 45° camera in reducing workload (reducing Mean Duration Joint OFF Time) occurs on the Switch Controller but not on the Master Controller. This is due to the greater alignment precision possible with the position command system, as opposed to the discrete, rather-difficult-to-coordinate, rate command system of the Switch Controller.

Examination of the plot of mean duration of joint "off" time plotted against displays (A) in Appendix C page C42, for E5 shows that workload is minimized under display combination A_2 where a 45° camera is present. However, there is no significant interactive effect as with E2. The reason for the superiority of this condensation is attributed to the presence of the 45°camera which displays information in both x, y and z axes. In condition A_3 (two orthagonal cameras) a scan must be set up between both displays to obtain such information while in combination A_1, no information in z is available.

6. Total Number of Joint Actuations

This parameter is a count of the number of control inputs made to each axis of control and is a further indicator of physical workload. As may be confirmed in Table VII it was not sensitive to changes in displays, with the exception of E4, Antenna Installation. As stated previously, this experiment was the only one where display combinations contained no view through a camera which was normal to the task-board, causing considerable variance in performing what was essentially an x, y alignment problem.

7. Subtask 1 Time

8. Subtask 2 Time

9. Subtask 3 Time

As indicated in Table V, each experiment has been broken down into 3 or less significant elements or subtasks. The times to complete these are recognized as dependent on the displays and controls but possibly with trends different than those of the complete experiment.

The effects of changing displays is, as shown on Table VII, significant to some of the subtasks of E2, Battery Replacement, E4, Antenna Installation, and E5, Fluid Coupling.

In E2, Battery Replacement, the Subtask 1 Time (Removal) was not affected because the operation was so simple – not needing more than a single normal display. The Subtask 2 Time (Installation) was a more complex operation requiring good alignment reference. This could only have been provided by a second camera.

In E4 (Antenna Installation) depth cues were crucial in Subtask 1 (Unlock and Disengage Connector) for accurately positioning the manipulator hand to rotate the latching handle and in Subtask 2 (Install Antenna and Extend Whip) for accurately aligning the antenna to achieve mating the coupling in its socket.

In E5, Fluid Coupling, the crucial tasks were in Subtask 1, aligning the male and female portions of the coupling and in Subtask 2 placement of the coupling lever on the release tab of the coupling.

10. Subtask 1 Errors

11. Subtask 2 Errors

12. Subtask 3 Errors

Error data was collected for each experiment except E1, Thruster Replacement, to add accuracy-of-performance data to the speed and workload data. An error was defined as any inadvertent imprecision of operation, such as hitting the mirror in an attempt to place it in the inspection compartment interior; failing to mate the antenna or hydraulic coupling due to misalignment; inadvertent scraping of the task-board, etc., i.e., an error was any unintended "clunk." Any observed error was recorded at the point in time it occurred and for distinguished right or left hand operation. This was done with a channel of the pen recorder in conjunction with an experimenter-operated event-marker.

Table VII shows that E4, Antenna Installation, was the only experiment which showed a significant variation in performance as a function of displays, and only for Subtask 2 (Install Antenna and Extend Whip). This subtask was essentially an x, y alignment problem; Figure 12 shows the nature of the relationship. Under condition A_1 (single normal camera) the camera allowed alignment in one axis while the existence of a physical guide virtually guaranteed it in the other. Under condition A_2 (single camera parallel in the vertical plane) alignment information was provided in the same axis as that which the physical guide was designed to aid. However, no alignment information was available in the other axis due to the absence of the camera normal to the task. This condition proved very difficult for the operator, and a trial and error technique was adopted, resulting in both the higher level of errors and variability evidenced in the graph. It should be added that in E5, Fluid Coupling, the operation proved impossible to perform with a single parallel camera, so a new condition using a mirror was substituted. This camera-mirror combination was very successful in reducing physical and mental workload.

However, it may be concluded that addition of cameras to a single camera normal to the task does not, except in special circumstances, significantly reduce performance errors.

The graphs for E5, Fluid Coupling, in Appendix C show that Mean Duration of Joint OFF Time is lowest for the single-camera/mirror combination (A_2). Also task completion time was lowest. The reason for the usefulness of this additional information may be its manner of presentation. Through its integrations into a single display there is a greater tendency to use it, the scanning distances being short. Similar information presented on a second display may be ignored because of: (1) smaller size of scanned display, (2) scanning distance involved.

4.1.2 Significance of Controllers

The results of the analyses of variances for the different controllers is given in Table VII under the columns labeled "B." For virtually every dependent variable, changes in the controllers produced significant performance changes and accounted for the major portion of experimentally induced variance in the study.

The following are considerations of each of the dependent variables:

1. Integrated Joint Movement Time

Significant variations in this parameter were noted for all experiments with the exception of left-hand operations in E5, Fluid Coupling. These operations, requiring the alignment of the male portion of the hydraulic coupling with the female, are essentially an x-y alignment task similar to aligning the thruster cluster in E1, Thruster Replacement, where controls did produce a significant effect. This discrepancy may be explained as follows. In E5 only x-y alignment was critical; in E1, x-y alignment plus alignment in roll, pitch and yaw were also necessary for correct coupling. Reference to each of the 5 graphs in Appendix C for this parameter reveals that the value for B_1 (Switch Controller) is always consistently lower than that for

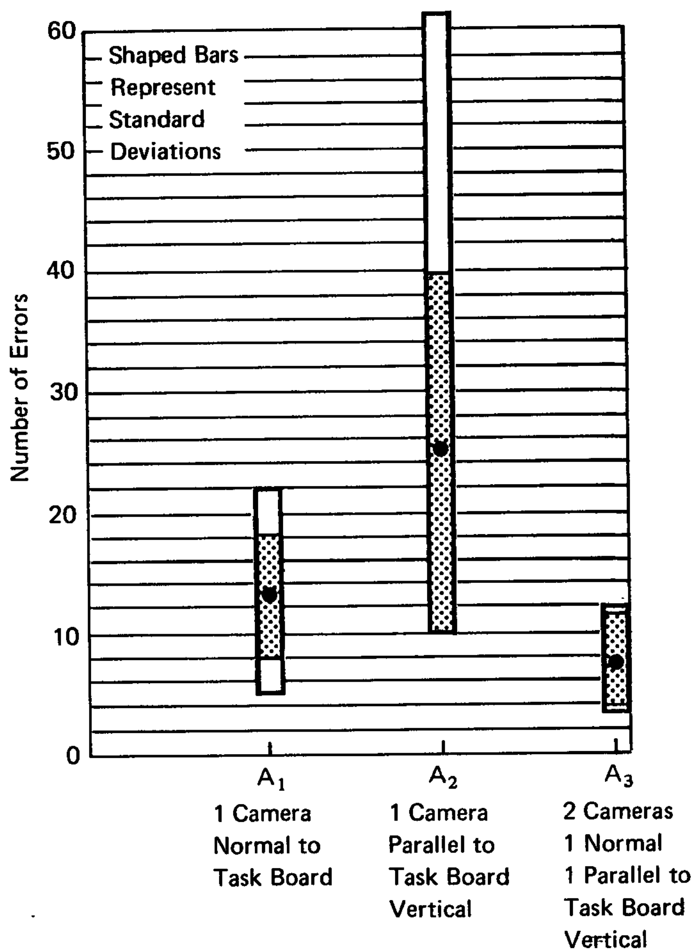


Figure 12. E4 Antenna Installation showing the Significant Variation in Errors as a Function of Display Variation

B_2 (Master Controller). This is expected since the switches allow greater economy of motion than the Master Controller. A given maneuver on the former rarely involves the coordination of more than three joints, and frequently only two; whereas on the latter, because the whole arm is moved, many joints may be actuated, increasing the Integrated Joint Movement Time.

Since B_3 (Levers) combines both rate and position control, one might expect the value for B_3 to fall between those for B_1 (Switch Controller) and B_2 (Master Controller). In E1, Thruster Replacement, E3, Compartment Inspection, and E4, Antenna Installation, this is the case. The Levers were not evaluated for E2, Battery Replacement because control reversals (para. 4.4.1.3) were so frequent that the operator could not achieve the level of consistency required in the training program. Therefore, after twenty trials without reaching the level of consistency, the lever controller was not used. In E5, Fluid Coupling, the values for B_2 and B_3 are approximately the same which may be because the particular task called largely for the use of the position command feature on the B_3 (Levers) making the controller functionally similar to B_2 (Master Controller).

2. Integrated Joint OFF Time

Predictably, the inverse of the relationships discussed above, existed for this parameter, and the explanation is the logical inverse of that above.

3. Time Moved/Time Not Moved Ratio

As demonstrated later using the multiple correlation data, this measure yields no information which is not inherent in the above two parameters from which it was derived.

4. Mean Duration of Joint Movement Time

Without exception, this parameter yielded significant variation across control configurations. This variation was also of a consistent nature. The Switch Controller always yielded the shortest Mean Duration of Joint Movement Time, the Master Controller the highest and the Levers in between. The rationale for this finding is not dissimilar from that for 1 and 2 above.

Observing the method of use of each of the control systems by the operator revealed the following. The separate digital nature of the Switch Controller forced the operator to use serial operations of the switches to produce a movement in the teleoperator manipulator arm, generally in the correct direction, but deviating either side of the ideal loci of motion. To minimize these deviations, switching durations tended to be kept short, the main exceptions being where pure pitch, roll or yaw were required. Pure linear motion, however, always called for coordinated "short-burst" switching among the appropriate joints.

The Master Controller exoskeleton required, of its nature, none of this; all motions being smooth, continuous and thus of longer duration. The Levers, combining both features, naturally fell between the two.

5. Mean Duration of Joint OFF Time

Results were very consistent across experiments, with the Switch Controller highest, the Master Controller lowest, and Levers in between on this parameter. The consistency of these results and those for 4 above suggest that hardware, as well as human performance considerations are at play. It may be concluded from this data that the Switch Controller posed the greatest mental workload. Also, according to this measure, the Master Controller yields the lowest mental workload, a result definitely concurred by the operator. The closeness of the values on this parameter for the Switch Controller and the Levers, also tend to confirm operator appraisal, since certain undesirable control characteristics of the Levers, e.g., high and uneven breakout forces and poor control made this a high workload device (see Section 4.3).

6. Total Number of Joint Actuations

As noted in the discussion of the effect of displays, and as is confirmed by correlation analysis, this measure is a particularly good measure of physical workload, defining as it does the total control inputs required to perform the task. As can be seen from Figure 13, which compares data on this parameter integrated across both hands for the manipulation experiments excluding E1, Thruster Replacement, B_1 (Switch Controller) yielded the highest number of joint actuations and the B_2 (Master Controller) was consistently lower. This is explicable in terms of similar arguments to those used in explaining 4 above – the digital serial "short burst" operation of the Switch Controller tending to produce more actuations of shorter duration than the continuous coordinated parallel operation of joints in the Master Controller. However, it will be observed in Figure 13 that there is considerable inconsistency in the data for B_3 (Levers). It goes from highest in E1, Thruster Replacement, to least in E4, Antenna Installation, and E5, Fluid Coupling, with an intermediate position in E3, Compartment Inspection. This is undoubtedly due to certain inherent weaknesses, not so much in the Levers as a control concept, but in their particular hardware implementation used in this study.

The high breakout forces and poor control had a more serious impact on some experiments than on others. Moreover, operator and experimenter observations tended to confirm a certain random element in response to control inputs in the Levers (Section 4.3), which would also contribute to the noted variability in the data.

7. Subtask 1 Time

8. Subtask 2 Time

9. Subtask 3 Time

Reference to Table VII confirms that, without exception, the particular control system used significantly affected speed of subtask performance, i.e., time taken to complete it. Reference to the graphs in Appendix B reveals the results to be highly consistent, with the Switch Controller always yielding slowest performance and the Master Controller the fastest. The result is due to inherent differences in operations, discrete serial operation being slower than continuous parallel operations of joints.

10. Subtask 1 Errors

11. Subtask 2 Errors

12. Subtask 3 Errors

Significant variations in performance errors were noted as a function of controls. Error data were not collected from E1, Thruster Replacement, but were from the other experiments. In E2, Battery Replacement, E3, Compartment Inspection, and E4, Antenna Installation, the Switch Controller consistently produced the greatest number of errors. In E5, Fluid Coupling, the Levers produced the greatest number. Why the Levers were worst in only one case is hard to account for, in view of their problems with path traceability and breakout forces. It is possible that the operator compensated by working harder to achieve accurate performance. The high level of errors with the Switch Controller is attributed to two factors: first, the impossibility of obtaining pure linear motion (only approximations being possible) and, second, the difficulty encountered by apparent control reversals in certain parts of the movement envelope, e.g., wrist roll reverses the switching direction of wrist pitch.

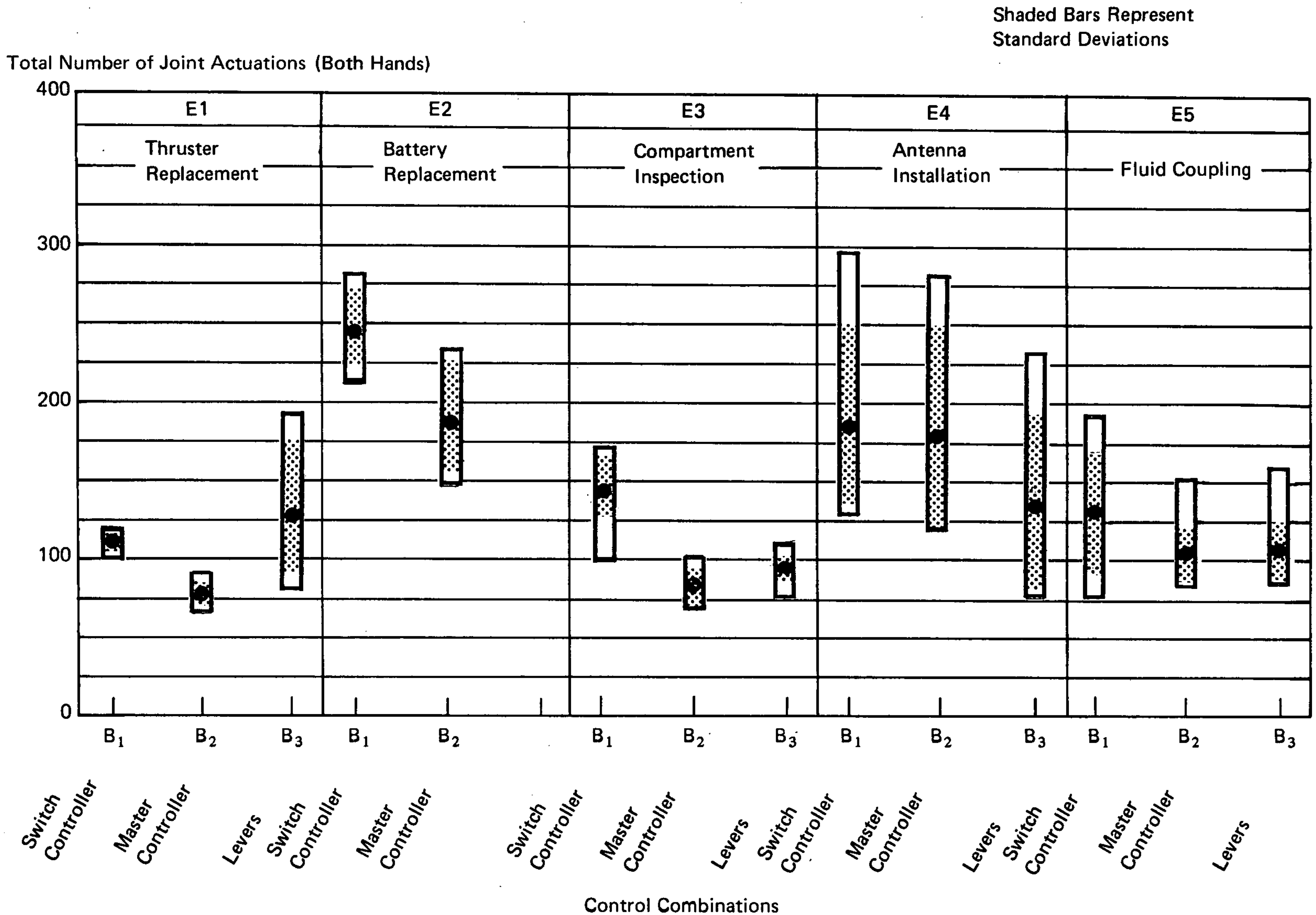


Figure 13. Total Number of Joint Actuations, Both Hands, as a Function of Control-System Changes, for each of the Five Experiments

In all cases, and not surprisingly, the Master Controller yielded the most error-free performance.

4.1.3 Subjective Data

Subjective data were collected at the end of E2, Battery Replacement, and again at the end of E5, Fluid Coupling.

The questions asked and the responses collected are set out below in Table VIII.

TABLE VIII.
RESULTS OF QUESTIONNAIRE

Question	Response	
	E1 Thruster Replacement E2 Battery Replacement	E3 Compartment Inspection E4 Antenna Installation E5 Fluid Coupling
1. How would you rank speed of performance for each control system from 1, highest, to 3, lowest?	1 Master Controller 2 Levers 3 Switch Controller	1 Master Controller 2 Levers 3 Switch Controller
2. How would you rank performance accuracy for each control system from 1, most accurate, to 3, least accurate?	1 Master Controller 2 Switch Controller 3 Levers	1 Master Controller 2 Switch Controller 3 Levers
3. How would you rank physical workload imposed by each control system from 1, least, to 3, greatest?	1 Switch Controller 2 Levers 3 Master Controller	1 Switch Controller 2 Levers 3 Master Controller
4. How would you rank mental workload imposed by each control system from 1, least, to 3, greatest?	1 Master Controller 2 Switch Controller 3 Levers	1 Master Controller 2 Switch Controller 3 Levers
5. Which was the most useful display combination, all things considered? A_1, A_2 or A_3?	A_3	A_3
6. You rated A_3 as most important. This combination is merely A_1 plus an additional 90° camera. How much additional help was this camera: 1. 100% 2. 75%, 3. 50%, 4. 25%, 5. $<$ 25%?	5	5

Examination of Table VIII shows perfect consistency between the two sets of ratings. Confidence in this consistency is increased because the two rating sessions were conducted three months apart. Now, it remains to examine how closely these assessments correlate with the objective measures in Table VII.

Question 1: Ratings of Speed of Performance correlates perfectly with the objective findings. The operator ranked each control system in the correct order.

Question 2: Performance accuracy ratings yielded a somewhat different result. There is agreement on the fact that the Master Controller yielded the most error-free operation, but disagreement as to which controller yielded the lowest level of performance in terms of errors. The operator consistently chose the Levers, but the data shows that in three out of the four cases the Switch Controller was worst. A possible explanation for this discrepancy is that the operator is confusing control difficulty with error-rate in rating performance.

Question 3: Perfect correspondence between subjective and objective assessment of workload would be surprising. Not only is subjective assessment inherently weak but objectively measuring the phenomena is difficult. It seems clear that the measures chosen for their correlation with physical workload, (i.e., Integrated Joint Movement Time and Total Number of Joint Actuations), are effected, at least partially, by inherent hardware characteristics. These characteristics might give rise to a subjective feeling of increased or decreased physical workload. Physical workload as indicated by Integrated Joint Movement Time, points to the Master Controller as the device producing the greatest physical workload; this finding is concurred by the operator who also rates it this way. Perfect correspondence also exists on this parameter with respect to the Switch Controller and the Levers, the former giving the lightest physical workload and the latter falling in between. However, when the subjective assessment of physical workload is compared with total Number of Joint Actuations, a measure which seemed to be a good indicator of physical workload, a different picture emerges. There is now a negative correlation with respect to the Switch Controller and Master Controller. The former is always higher on the joint actuation scale than the latter, indicating a higher physical workload level for the Switch Controller. The fluctuation of the performance of Levers, across experiments, makes correlation with the subjective ratings impossible. Overall, the usefulness of joint actuations as an indicator of physical workload, saying in effect that high-frequency operations produce heavier physical workload than low frequency operations is a valid one. Integrated Joint Movement Time is also a good measure of workload by measuring total energy input and has the advantage of perfect subjective confirmation.

Question 4: The objective measures used as indicators of mental workload were Integrated Joint Off Time and Mean Duration of Joint Off Time. The former measure indicates the Master Controller to be the device imposing the lightest mental workload, and this is also the subjective finding of the operator. Disagreement between objective data and ratings does exist on which controller, Switch or Levers, imposes the heaviest mental workload. According to the Integrated Joint Off Times, the Switch Controller is worst. It is possible that the operator is remembering one small (in terms of operation time) but very serious limitation of the Levers in reaching this rating, i.e., the rate-controls governing wrist pitch, wrist roll and fingers. Frequent reverse control inputs were noted for these on the Levers and they required great concentration to avoid. However, the use of the rate controls on the Levers was usually limited to short operations at the end of a subtask, whereas all operations on the Switch Controller involved rate control, but with fewer of the reversal and breakout problems associated with the Levers.

Mean Duration of Joint Off Time also corroborates the operator rating of least mental workload for the Master Controller, since the time is lowest for that controller. However the same discrepancy over the positions of the Switch Controller and Levers exists, the mean time being highest for the former, while the latter are rated by the operator as imposing the greatest workload.

Questions 5 and 6: The operator rated display combination A_3 as the most useful. This combination consisted in all experiments of one camera normal to the task board and one camera at 90° (parallel) to it in the horizontal plane for the first three experiments and in the vertical plane for the other two. However, in answering Question 6 the operator rated the increment of utility added to the normal camera by the 90° camera at the lowest rating available <25%. The data bears out both of these conclusions, showing the 90° camera helped significantly in E4, antenna installation, where a special alignment problem was involved but that in the other experiments, the contribution of the second camera was small.

4.1.4 Multiple Correlation Analysis

To determine the uniqueness of the objective performance measures (dependent variables) chosen for the research program, a multiple correlation analysis of collected data for all experiments was conducted, using a RAX computer program for the Pearson Product Moment Correlation Coefficient. A typical computer printout is presented in Table IX. On the completion of all the analyses, a summary matrix was prepared and is presented in Table X. This table shows the degree of association between all pairs of dependent variables,

TABLE IX

A TYPICAL CORRELATION ANALYSIS - MANIPULATION EXPERIMENT

```
 /id anov 073583818450500

M.0076 RAX IS IN CONTROL, SIGN ON.
/id anov 073583818450500
M.0073  ACTION IN PROGRESS
M.0072  BEGIN
/input
/include stat
/endrun



 IS A CORRELATION ANALYSIS DESIRED.(YES OR NO)
yes

INPUT THE NUMBER OF VARIABLES(M.LE.20) AND THE NO.OF OBSERVATIONS(N.LE.60).(M,N)

10,16

INPUT THE  16 OBSERVATIONS FOR EACH OF THE  10 VARIABLES.ONE SET OF OBSERVATIONS PER LINE


2.63,2.69,2.96,3.2,2.8,3.19,2.62,2.32,3.38,6.64,5.6,5.68,4.66,6.37,7.23,4.8,
7.52,7.15,
29.77,22.41,28.23,27.99,26.58,27.61,28.97,24.77,35.22,7.24,7.,7.15,7.94,6.58,
8.17,8.26,6.36,6.5,
.2,.12,.105,.114,.106,.115,.09,.094,.096,.917,.8,.794,.587,.969,.884,.581,
1.18,1.1,
1.066,1.214,1.304,1.264,1.183,1.485,1.111,1.043,1.308,3.068,2.361,1.753,
1.358,3.606,3.338,1.364,3.213,3.36,
13.547,10.311,13.108,12.584,11.779,14.423,13.908,10.857,15.905,3.388,3.215,
2.607,2.797,3.234,4.059,2.893,2.591,2.91,
272.,208.,243.,210.,244.,222.,250.,220.,256.,146.,159.,206.,212.,125.,147.,
226.,157.,143.,
2.08,2.23,2.27,2.28,2.47,2.58,2.43,2.47,2.9,1.,.9,1.07,.917,.88,.88,.933,.78,
.9,
3.32,1.95,2.93,2.91,2.5,2.55,2.83,2.05,3.53,.983,.0,.933,.883,.967,1.32,.933,
M.0064 LINE TOO LONG, RETRANSMIT.
3.32,1.95,2.93,2.91,2.5,2.55,2.83,2.05,3.53,.983,.9,.933,.883,.967,1.32,.933,
1.2,1.05,
3.,4.,3.,9.,5.,5.,5.,9.,8.,0.,1.,1.,1.,3.,2.,1.,2.,1.,
12.,7.,10.,9.,6.,6.,11.,6.,13.,1.,0.,2.,1.,3.,3.,3.,2.,5.,
```

CORRELATION COEFFICIENT MATRIX

	1	2	3	4	5	6	7	8	9	10	
1	1.0000										INTEGRATED JOINT MOVEMENT TIME
2	-0.8827	1.0000									INTEGRATED JOINT OFF TIME
3	0.9785	-0.9263	1.0000								TIME MOVED: TIME NOT MOVED RATIO
4	0.9233	-0.7423	0.8949	1.0000							MEAN DURATION OF JOINT MOVEMENT TIME
5	-0.8601	0.9938	-0.9105	-0.6984	1.0000						MEAN DURATION OF JOINT ''OFF'' TIME
6	-0.8684	0.8122	-0.8578	-0.9287	0.7726	1.0000					TOTAL NUMBER OR JOINT ACTUATIONS
7	-0.8904	0.9758	-0.9340	-0.7434	0.9729	0.7677	1.0000				SUBTASK 1 TIME
8	-0.7812	0.9739	-0.8362	-0.6408	0.9695	0.7722	0.9093	1.0000			SUBTASK 2 TIME
9	-0.6803	0.7840	-0.7295	-0.5289	0.7667	0.4805	0.8194	0.7239	1.0000		SUBTASK 1 ERRORS
10	-0.6803	0.7840	-0.7295	-0.5289	0.7667	0.4805	0.8194	0.7239	1.0000	1.0000	SUBTASK 2 ERRORS

FOLDOUT FRAME 1

FOLDOUT FRAME 2

TABLE X

SUMMARY SHEET CORRELATION ANALYSIS

DEPENDENT VARIABLES

DEPENDENT VARIABLES	1 Integrated Joint Movement Time		2 Integrated Joint Off Time		3 Time Moved: Time Not Moved Ratio		4 Mean Duration of Joint Movement Time		5 Mean Duration of Joint "OFF" Time		6 Total Number of Joint Actuations	
Experiment →	LH E1 E2 E3 E4 E5	RH E1 E2 E3 E4 E5	LH E1 E2 E3 E4 E5	RH E1 E2 E3 E4 E5	LH E1 E2 E3 E4 E5	RH E1 E2 E3 E4 E5	LH E1 E2 E3 E4 E5	RH E1 E2 E3 E4 E5	LH E1 E2 E3 E4 E5	RH E1 E2 E3 E4 E5	LH E1 E2 E3 E4 E5	RH E1 E2 E3 E4 E5
1 Integrated Joint Movement Time												
2 Integrated Joint Off Time	-0.570** -0.230 -0.788*** 0.084	-0.769*** -0.883*** -0.743*** -0.239 -0.348										
3 Time Moved: Time Not Moved Ratio	0.841*** 0.902*** 0.900*** 0.819***	0.940*** 0.978*** 0.832*** 0.713*** 0.740***	-0.884*** -0.460* -0.899*** -0.477*	-0.877*** -0.926*** -0.913*** -0.761*** -0.840***								
4 Mean Duration of Joint Movement Time	0.888*** 0.940*** 0.330 0.326	0.867*** 0.920*** 0.581** 0.434* 0.544**	-0.670*** -0.262 -0.264 -0.134	-0.639*** -0.742*** -0.339 -0.420* -0.608***	0.895*** 0.848*** 0.379 0.334	0.855*** 0.895*** 0.377 0.637*** 0.759***						
5 Mean Duration of Joint "OFF" Time	-0.253 0.112 -0.440* 0.143	-0.536** -0.860*** -0.561** -0.228 -0.518**	0.685*** 0.497** 0.631*** 0.320	0.730*** 0.994*** 0.688*** 0.757*** 0.757***	-0.567** -0.209 -0.681*** 0.028	-0.694*** -0.910*** -0.746*** -0.662*** -0.809***	-0.237 0.269 -0.219 0.281	-0.302 -0.698*** 0.118 -0.235 -0.413*				
6 Total Number of Joint Actuations	-0.558** 0.726*** -0.721*** 0.393*	-0.555** -0.868*** -0.238 0.478* 0.382	0.412* 0.182 0.919*** 0.342	0.203 0.812*** 0.475* 0.681*** 0.511**	-0.639*** 0.471 -0.762*** 0.156	-0.445* -0.858*** -0.272 -0.144 -0.107	-0.758*** 0.583** -0.230 -0.471*	-0.735*** -0.929*** -0.094 -0.099 -0.184	0.238 0.122 0.383 -0.165	-0.131 0.773*** -0.160 0.396 -0.003		
7 Subtask 1 Time	-0.595** -0.829*** -0.819*** -0.133	-0.774*** -0.890*** -0.734*** -0.526** 0.239	0.948*** 0.471* 0.888*** 0.561**	0.962*** 0.976*** 0.886*** 0.873*** 0.763***	-0.851*** -0.726*** -0.900*** -0.380	-0.876*** -0.934*** -0.923*** -0.842*** -0.423*	-0.651*** -0.847*** -0.433* -0.187	-0.648*** -0.743 -0.294 -0.390* -0.315	0.643*** -0.099 0.618*** -0.184	0.711*** 0.973*** 0.718*** 0.566** 0.446*	0.403* -0.651*** 0.830*** 0.121	0.221 0.768*** 0.269 0.378 0.697
8 Subtask 2 Time	-0.495** -0.687*** -0.432* 0.034	-0.655*** -0.780*** -0.276 0.273 -0.482*	0.932*** 0.636*** 0.596** 0.341	0.857*** 0.974*** 0.632*** 0.813*** 0.895***	-0.831*** -0.625*** -0.583*** -0.150	-0.816*** -0.836*** -0.577** -0.378 -0.836***	-0.652*** -0.707*** -0.076 -0.403*	-0.630*** -0.641*** -0.075 -0.244 -0.613***	0.619*** 0.029 0.575** -0.233	0.627*** 0.969*** 0.238 0.748*** 0.717***	0.392* -0.532** 0.484* 0.592**	0.155 0.772*** 0.549** 0.840*** 0.319
9 Subtask 3 Time	-0.719***	-0.650***	0.975***	0.939***	-0.841***	-0.812***	-0.213	-0.305	0.607***	0.656***	0.882***	0.414
10 Subtask 1 Errors	-0.571** -0.396* 0.260	-0.680*** 0.017 -0.176 0.581**	0.474* 0.286 -0.104	0.784*** -0.199 0.608*** 0.359	-0.524** -0.424* 0.302	-0.729*** 0.145 -0.365 -0.014	-0.600*** -0.611*** 0.462*	-0.529** 0.128 -0.189 -0.014	-0.075 0.208 -0.040	0.767*** -0.165 0.281 0.092	-0.423* 0.207 -0.251	0.480* -0.158 0.498** 0.561**
11 Subtask 2 Errors	-0.648*** -0.144 0.023	-0.719*** -0.053 0.090 0.397*	0.644*** 0.349 0.312	0.907*** 0.167 0.841*** 0.369	-0.625*** -0.206 -0.155	-0.757*** -0.141 -0.412* -0.496**	-0.677*** -0.083 -0.305	-0.579** 0.013 -0.117 -0.294	0.012 0.184 -0.321	0.896*** -0.183 0.773*** 0.271	-0.445* 0.313 0.239	0.733*** 0.595** 0.741 -0.083
12 Subtask 3 Errors	-0.565**	-0.496**	0.881***	0.592**	-0.674***	-0.606***	-0.155	-0.157	0.463*	0.579**	0.869***	0.193

DEPENDENT VARIABLES	7 Subtask 1 Time		8 Subtask 2 Time		9 Subtask 3 Time		10 Subtask 1 Errors		11 Subtask 2 Errors		12 Subtask 3 Errors	
Experiment →	LH E1 E2 E3 E4 E5	RH E1 E2 E3 E4 E5	LH E1 E2 E3 E4 E5	RH E1 E2 E3 E4 E5	LH E1 E2 E3 E4 E5	RH E1 E2 E3 E4 E5	LH E1 E2 E3 E4 E5	RH E1 E2 E3 E4 E5	LH E1 E2 E3 E4 E5	RH E1 E2 E3 E4 E5	LH E1 E2 E3 E4 E5	RH E1 E2 E3 E4 E5
1 Integrated Joint Movement Time												
2 Integrated Joint Off Time												
3 Time Moved: Time Not Moved Ratio												
4 Mean Duration of Joint Movement Time												
5 Mean Duration of Joint "OFF" Time												
6 Total Number of Joint Actuations												
7 Subtask 1 Time												
8 Subtask 2 Time	0.787*** 0.909*** 0.551** 0.468*	0.787*** 0.909*** 0.551** 0.445* 0.468*										
9 Subtask 3 Time	0.787***	0.787***	0.486*	0.486*								
10 Subtask 1 Errors	0.819*** 0.499** 0.086	0.819*** -0.290 0.589** 0.848***	0.724*** 0.357 -0.305	0.724*** 0.263 0.398* 0.051	0.165	0.169						
11 Subtask 2 Errors	0.831*** 0.200 0.490**	0.831*** 0.217 0.595** 0.221	0.944*** 0.216 0.321	0.944*** 0.288 0.876*** 0.322	0.657*** 0.371 -0.002	0.657*** 0.049 0.555** 0.095	0.158	-0.157				
12 Subtask 3 Errors	0.654***	0.697***	0.522**	0.162	0.905***	0.571**	0.135	-0.160	0.406*	0.311		

* Significant $\alpha \leq 0.05$
** Significant $\alpha \leq 0.01$
*** Significant $\alpha \leq 0.0001$

for each experiment and for both teleoperator hands (except E5, Fluid Coupling, where only the right hand was used). A considerable percentage of these correlation coefficients showed consistency across experiments and many were significant statistically.

To simplify the process where some dependent variables could be eliminated due to high correlation with one or more other variables, certain criteria were established and a new summary table, Table XI, was completed. This table was prepared as follows: Correlation coefficients in Table X for each five-experiment group were examined for consistency and significance. Consistency required that all five coefficients be of the same sign, and significance required that all five be not only of the same sign but also statistically significant at $\alpha \leqslant 0.05$. Both these latter criteria had to be met for inclusion in Table XI. The groups meeting these criteria were averaged and the average coefficient entered into Table XI. Groups failing to meet the criteria were labeled NC (Not Consistent and/or some observations not significant) or NS (No Coefficient Significant).

Examination of Table XI reveals the following:

Time Moved/Time Not Moved ratio may be eliminated from future research since it correlates highly with both Integrated Joint Movement Time (positive correlation) and with Integrated Joint Off Time (negative correlation).

For right hand operations, and these accounted for a major proportion of manipulator activity, high positive correlations are noted between Integrated Joint Movement Time and Mean Duration of Joint Movement time and between Integrated Joint Off Time and Mean Duration of Joint Off Time, thus one pair may be eliminated. Subjective data discussed in the previous section, indicate Integrated Joint Movement Time to be more reliable than Mean Duration of Joint Movement Time and thus the latter should be eliminated. However, rating data indicate Integrated Joint Off Time and Mean Duration of Joint Off Time, to be similarly predictive. Mean Duration of Joint Off Time might therefore be eliminated for computational simplicity.

Total Number of Joint Actuations correlated significantly and consistently with nothing, and is therefore a unique performance measure as an indicator of physical workload.

Subtask times tended to be highly correlated with Integrated Joint Off Time and Mean Duration of Joint Off Time. However, since direct information on speed of performance is of itself important, abandonment of this measure would not be recommended.

Task errors correlated significantly and with no other variable. Therefore, they are unique measures of accuracy.

C.2.

TABLE XI

AVERAGES(1) FOR CONSISTENT CORRELATIONS OF DEPENDENT VARIABLES ACROSS EXPERIMENTS

	Dependent Variables	1 LH	1 RH	2 LH	2 RH	3 LH	3 RH	4 LH	4 RH	5 LH	5 RH	6 LH	6 RH
1	Integrated Joint Movement Time												
2	Integrated Joint Off Time	NC	NC										
3	Time Moved: Time Not Moved Ratio	0.865	0.841	-0.680	-0.863								
4	Mean Duration of Joint Movement Time	NC	0.669	NC	NC	NC	NC						
5	Mean Duration of Joint "OFF" Time	NC	NC	NC	0.785	NC	-0.764	NS	NC				
6	Total Number of Joint Actuations	NC	NC	NC	NC	NC	NC	NC	NC	NS	NC		
7	Subtask 1 Time	NC	NC	0.717	0.892	-0.714	-0.800	NC	NC	NC	0.683	NC	NC
8	Subtask 2 Time	NC	NC	NC	0.834	NC	-0.689	NC	NC	NC	NC	NC	NC
9	Subtask 3 Time	-0.719*	-0.650*	0.975*	0.939*	-0.841	-0.812*	NS	NS	0.607*	0.656*	0.882	NS
10	Subtask 1 Errors	NC	NC	NC	NC	NC	NC	NC	NC	NS	NC	NC	NC
11	Subtask 2 Errors	NC	NC	NC	NC	NC	NC	NC	NC	NS	NC	NC	NC
12	Subtask 3 Errors	-0.565*	-0.496*	0.881*	0.592*	-0.674*	-0.606*	NS	NS	0.463*	0.579*	0.869*	NS

	Dependent Variables	7 LH	7 RH	8 LH	8 RH	9 LH	9 RH	10 LH	10 RH	11 LH	11 RH	12 LH	12 RH
1	Integrated Joint Movement Time												
2	Integrated Joint Off Time												
3	Time Moved: Time Not Moved Ratio												
4	Mean Duration of Joint Movement Time												
5	Mean Duration of Joint "OFF" Time												
6	Total Number of Joint Actuations												
7	Subtask 1 Time												
8	Subtask 2 Time	0.679	0.632										
9	Subtask 3 Time	0.787*	0.787*	0.486*	0.486*								
10	Subtask 1 Errors	NC	NC	NC	NC	NS	NS						
11	Subtask 2 Errors	NC	NC	NC	NC	NC	NC	NS	NS				
12	Subtask 3 Errors	0.654*	0.697*	0.522*	NS	0.905*	0.571*	NS	NS	0.406*			

* Unreliable, 1 Sample Only
NC Not Consistent
NS No Significant Observation
(1) To be Averaged, All Correlation Coefficients had to be Significant and of the Same Sign.
LH = Left Hand
RH = Right Hand

4.2 EVALUATION OF MANEUVERING TASKS

An experimental approach similar to that used in the manipulation experiments was used to evaluate maneuvering tasks. Data from recorder traces and video tapes were reduced to the format shown in Table XII. The data were then analyzed using the same analysis-of-variance computer program. As in the preceding section, displays are labeled as A, A_1 being a single TV monitor showing a view directly ahead of the RMU plus two meter type indicators displaying R and $\dot{R}$; and A_2 being the single TV monitor only. Control dynamics are always labeled B, B_1 being acceleration command and B_2 being rate command. Label C throughout was docking aids, C_1 being gun sight only and C_2 being reticle only. Each combination of system hardware (independent variables) was tested 3 times.

The few significant main effects and interactions revealed by the analyses are summarized in TAble XIII. All significant results depicting functional relationships between the variables were plotted. These plots are included in Appendix C.

It should be mentioned here that all runs regardless of combinations of displays control dynamics and docking aids concluded with a successful docking on the first trial.

4.2.1 Significance of Displays(A)

An examination of Table XIII confirms that none of the 16 dependent variables responded significantly to changes in Displays alone. The addition of R and $\dot{R}$ displays did not improve or degrade maneuvering and docking performance. This would indicate that sufficient R and $\dot{R}$ cues are available from stadia rings on the TV monitor at the close ranges (<25 ft) being employed. From these distances crude R and $\dot{R}$ information can be obtained from the size and rate of change of the image on the TV raster. With extensive experience, the operator adapts and uses this information to compensate for the missing displays.

However, long-range rendezvous simulations (Reference 1) have shown that, for many small targets at ranges greater than 100 ft, range and range rate cues are no longer available, and closing velocities from these longer ranges tend to be higher. R and R displays under these conditions become imperative to allow sufficient time to retro-thrust and eliminate the possibility of catastrophic impacts. Effects of R & R displays were also found in significant interactions with other independent variables.

The triple interaction of Displays, Control Dynamics and Docking Aids (A x B x C) is a typical example. This interaction produced significant variations in the instantaneous docking velocity $\dot{R}$. In view of this interaction, $\dot{R}$ was plotted against displays A. The plot in Figure 14 shows the mean value of docking velocity without R and $\dot{R}$ (Display A_2) to be only slightly higher than with them. There is, however, greater variability in performance as indicated by the range. The desirable $\dot{R}$ at docking is in the range 0.1 - 0.2 ft/sec. In the experiments, this was exceeded 11 out of 12 times with the R and $\dot{R}$ displays but never by more than 0.1 ft/sec. Without the displays the number of times the desired upper limit was exceeded was 9, but in two instances the $\dot{R}$ was about twice the desired upper limit. Such maneuvers constitute a hazard to both the teleoperator and the

Reference 1 – Stewart, R.A., et al, "A Study of a Dual Purpose Maneuvering Unit (U)," AFAPL - TR-67-37, April 1967.

TABLE XII
DATA REDUCED FROM RECORDER TRACES AND VIDEO TAPES

		Dependent Variables															
		Energy Expend (%)		Translation						(ϵ_{range})		Docking (Instantaneous)					
Run	Code	Fuel	Batt	$(\dot{R})$ (ft/sec)	$\dot{R}_{peak}$ (ft/sec)	(ϵ_p) (deg)	(ϵ_y) (deg)	(ϵ_r) (deg)	(y) (ft)	Circ (ft)	Insp (ft)	$\dot{R}$ (ft/sec)	(ϵ_p) (deg)	(ϵ_y) (deg)	(ϵ_r) (deg)	(y) (in.)	Total Time (sec)
1	A1B2C1R1	44	11	0.26	0.42	2.3	0.6	1.6	0.6	0.43	1.5	0.30	1.0	5	2.0	0	280
2	A1B2C2R1	27	11	0.28	0.48	1.4	0.2	3.8	1.4	1.86	0.75	0.21	1.0	10	2.0	0	240
3	A2B2C1R1	51	20	0.42	0.63	9.5	0.2	2.9	0.2	2.20	1.20	0.42	0.5	0	16.0	0	302
4	A1B2C1R2	39	10	0.29	0.48	7.2	1.2	4.0	0.9	1.65	1.87	0.30	1.0	5	12.0	0	242
5	A2B2C2R2	33	9	0.38	0.66	9.9	2.4	0.6	1.1	0.82	2.25	0.30	0.5	5	6.0	0	194
6	A1B2C1R2	23	10	0.27	0.42	6.3	0.7	4.9	0.8	1.35	0.82	0.21	0	3	6.0	0	209
7	A2B2C2R3	31	8	0.24	0.42	6.3	0.8	1.1	0.4	0.97	1.95	0.39	0.5	3	4.0	0	247
8	A1B2C2R2	45	12	0.26	0.42	6.3	1.1	1.8	1.1	0.37	0.15	0.30	1.0	1	5.0	2	298
9	A2B2C1R1	27	7	0.36	0.51	7.7	1.0	0.4	1.0	0	0.52	0.27	1.0	3	3.0	0	220
10	A2B2C1R3	25	8	0.29	0.45	6.8	0	0.5	2.1	1.42	0.38	0.24	0	7	0	1	219
11	A1B2C2R3	27	8	0.27	0.54	8.1	0.9	0.7	1.5	1.23	0.68	0.24	0	2	5.0	0	252
12	A2B2C1R2	27	6	0.35	0.42	6.3	0.8	0.3	2.8	1.57	1.95	0.18	1.0	3	2.0	2	233
13	A1B1C1R1	47	7	0.22	0.45	2.8	4.8	0.4	1.5	0.56	1.86	0.18	1.0	3	4.0	2	302
14	A1B1C1R2	46	8	0.17	0.42	5.9	3.7	0.8	1.2	0.32	0.75	0.21	1.0	10	1.0	0	320
15	A2B1C2R2	48	7	0.18	0.39	2.4	1.6	1.4	0.6	0.75	0.37	0.24	0	5	6.0	0	273
16	A2B1C1R2	41	6	0.37	0.54	2.2	2.2	1.6	0.7	1.50	3.00	0.24	2.0	5	8.0	1	273
17	A2B1C2R1	32	5	0.34	0.66	7.0	3.3	0.4	1.1	1.65	3.41	0.18	1.0	0	1.0	0	244
18	A1B1C2R2	36	6	0.27	0.42	10.0	3.2	0.6	2.1	0.97	1.50	0.21	1.0	2	0	1	254
19	A2B1C1R1	33	5	0.32	0.48	10.0	2.8	4.5	2.1	0.90	0.75	0.24	1.0	6	20.0	1	247
20	A1B1C1R3	25	4	0.32	0.45	5.0	2.5	0.4	1.2	0.49	0.37	0.21	1.0	0	2.0	2	215
21	A1B1C2R1	42	6	0.26	0.60	10.0	0.9	2.5	1.1	0.90	0.9	0.30	1.5	3	4.0	2	244
22	A2B1C1R3	39	5	0.20	0.39	6.0	4.1	0.2	0.8	0.97	0.9	0.24	1.0	1	4.0	1	255
23	A1B1C2R3	45	6	0.33	0.48	11.0	2.8	0.4	0.3	0.82	1.65	0.24	0	5	5.0	2	270
24	A2B1C1R3	37	7	0.29	0.48	4.0	4.5	0.8	0.3	0.82	0.62	0.18	0	3	5.0	1	234

CODE:

$(\dot{R})$ = Mean Velocity

$\dot{R}_{peak}$ = Maximum Velocity Achieved

ϵ_p = Mean Pitch Deviation (from LOS)

ϵ_y = Mean Yaw Deviation (from LOS)

ϵ_r = Mean Roll Deviation (from LOS)

(ϵ_{range}) = Mean Deviation in Range (from the ideal path)

Circ = Circumnavigation Maneuver

Insp = Inspection Maneuver

Y = Mean Lateral Deviation from the LOS Path

y = Mean Lateral Offset of Probe at the Instant Contact is Made

TABLE XIII
SUMMARY OF THE ANALYSIS OF VARIANCE RESULTS FOR THE MANEUVERING EXPERIMENT

	Energy Expenditure		Translation						
	Fuel	Electrical	$(\dot{R})$	$\dot{R}_{peak}$	(ϵ_p)	(ϵ_y)	(ϵ_r)	(Y)	Total Time
	% Used	% Used	ft/sec	ft/sec	(Deg)	(Deg)	(Deg)	(ft)	
A Displays	NS	NS	NS	NS	NS	NS	NS	NS	NS
B Control Dynamics	NS	**	NS	NS	NS	***	NS	NS	NS
C Docking Aids	NS	NS	NS	NS	NS	NS	NS	NS	NS
A x B	NS	NS	NS	NS	*	NS	*	NS	NS
A x C	NS	NS	NS	NS	NS	NS	NS	NS	NS
B x C	NS	NS	NS	NS	NS	NS	NS	NS	NS
A x B x C	NS	NS	NS	NS	NS	NS	*	NS	NS

	E_{Range}		Docking (Instantaneous)					
	Circ	Insp	$\dot{R}$	(ϵ_p)	(ϵ_r)	(ϵ_r)	(y)	Total Time
	ft	ft	ft/sec	Deg	Deg	Deg		
A	NS	NS	NS	NS	NS	NS	NS	NS
B	NS	NS	**	NS	NS	NS	*	NS
C	NS	NS	*	NS	NS	NS	NS	NS
A x B	NS	NS	NS	NS	NS	NS	NS	NS
A x C	NS	NS	NS	NS	NS	NS	*	NS
B x C	NS	NS	NS	NS	NS	NS	NS	NS
A x B x C	NS	NS	*	NS	NS	*	NS	NS

CODE:

NS = Not Significant
* = $\alpha \leqslant 0.05$
** = $\alpha \leqslant 0.01$
*** = $\alpha \leqslant 0.001$

A = Displays
B = Controls
C = Docking Aids

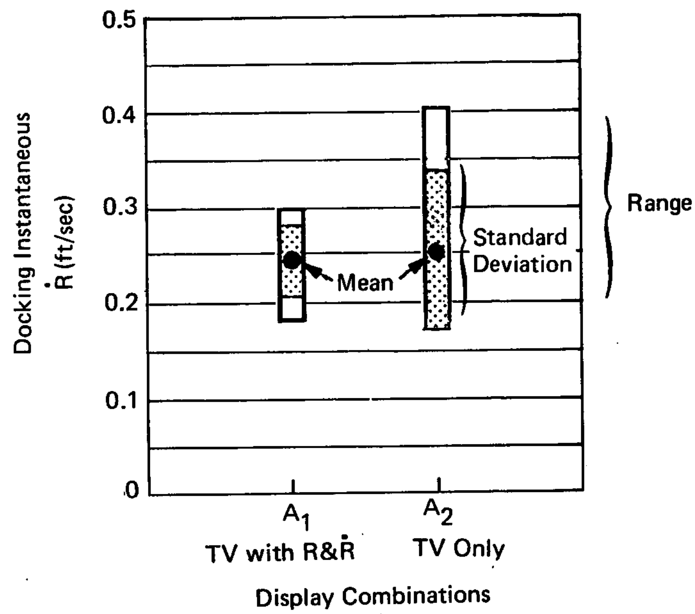


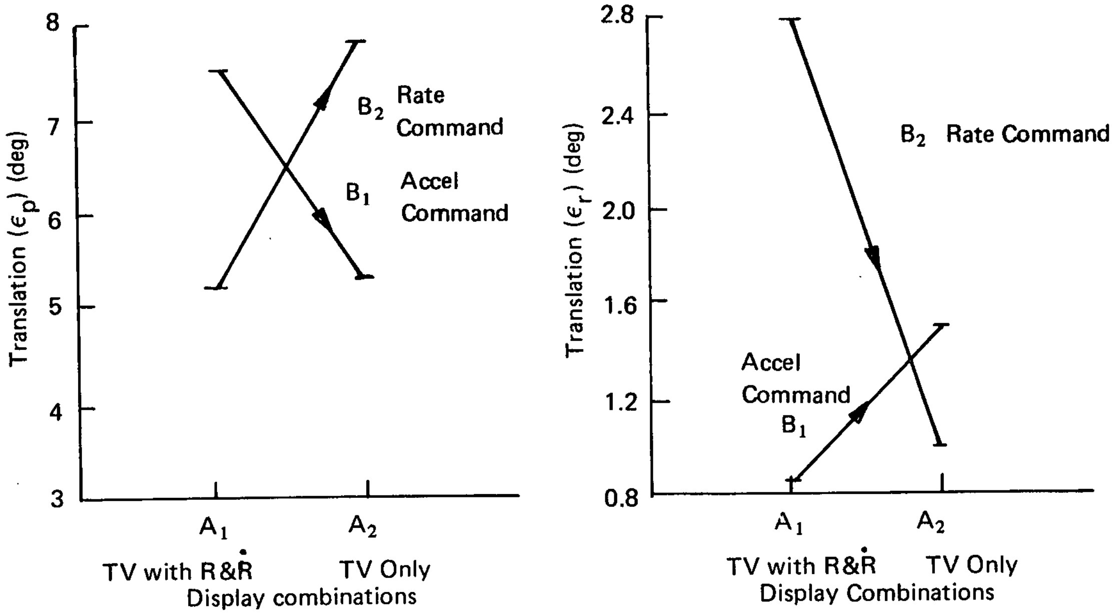
Figure 14. Variability in Docking
Velocity versus Displays

work site. If only one docking at excessive speed is avoided in space, by including R and Ṙ displays, then their presence is justified regardless of overall statistical difference.

The above conclusion is entirely concurred with by the operator who claims that their presence greatly reduces workload. Had it been possible to record control activity, a significant effect across displays might thus have been observed.

Two other significant interactions throw further light on the importance of Displays in the absence of significant separate main effects. These are the interactions of Displays and Control Dynamics (A x B) during translations on the mean pitching error (ϵ_p) and the mean roll error (ϵ_r). Plots of these interactions are shown in Figure 15. These graphs indicate that when acceleration command (B_1) is used the mean pitching error (ϵ_p) is greater with R and Ṙ displays (A_1) than without them. When rate command (B_2) is used the mean pitching error is less with R and Ṙ displays. The effect of the interaction on mean roll error (ϵ_r) is just the reverse.

The observed interactions may have been created by operator technique. When using the acceleration control system, small errors in roll or pitch attitude were accepted without correction, to avoid the added workload and prevent upsetting control moments that would be created by attempting a correction. The small errors integrated over a long time period could have results in statistically large random error measurements.



NOTE: The plotted points are joined by lines to indicate directionality not continuity, thus making clear rhe nature of the interactions.

Figure 15. Interactions of Controls (B) and Displays (A)

4.2.2 Significance of Control Dynamics (B)

Four dependent variables responded significantly to changes in Control Dynamics. These are

(1) Electrical energy expenditure

(2) Mean yawing error during translation (ϵ_y)

(3) Instantaneous docking velocity ($\dot{R}$)

(4) Probe positioning at docking (y)

Electrical energy expenditure was found to be significantly higher for the rate command system (B_2) than the acceleration command system (B_1) as shown in Figure 16. This indicates that the elecrical energy expenditure required to drive the Control Moment Gyros (part of the rate system) is consistently greater than the energy required to provide the additional pulses of the thruster valves for direct attitude control.

Mean yawing error during translation (ϵ_y) is plotted against control dynamics in Figure 17. The graphs show a significant reduction in yawing error with the rate-command system. This is a direct result of the position-hold feature incorporated in the rate-command system. The operator rated the acceleration command system as inferior to rate command with respect to workload, confirming the results.

Docking velocity ($\dot{R}$) was also found to be significantly affected by Control Dynamics. Figure 18 shows that docking rates are significantly higher using the rate-command system.

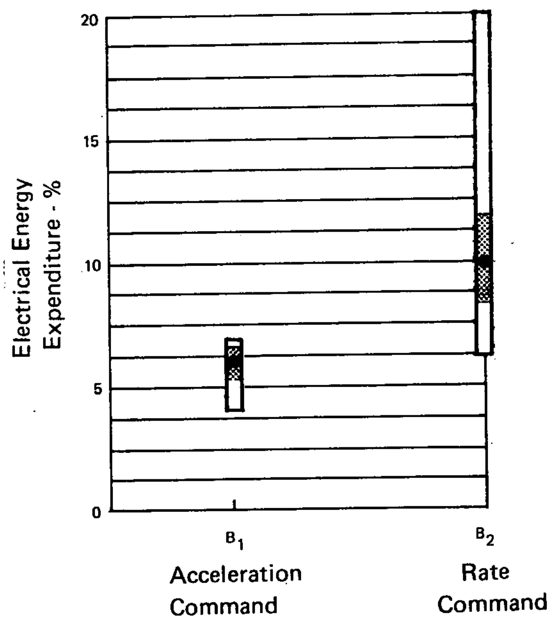


Figure 16. Energy Expenditure for Acceleration Command B_1 and Rate Command B_2

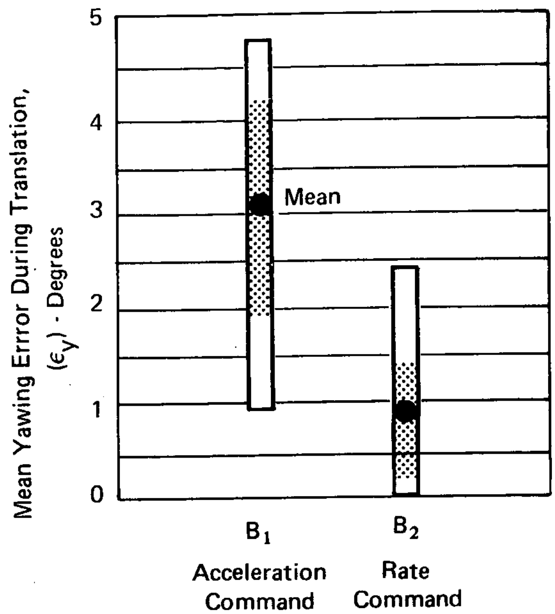


Figure 17. Mean Yawing Error During Translation

This attributed to the superiority of the rate control system which led the operator to higher confidence levels and hence, less concern for velocity control.

Finally probe positioning error at docking, ie., first contact of the boom with the docking cone, was found to be a significant function of control dyanmics, with the error (miss distance from the center of the cone) reduced when the rate command system was used.

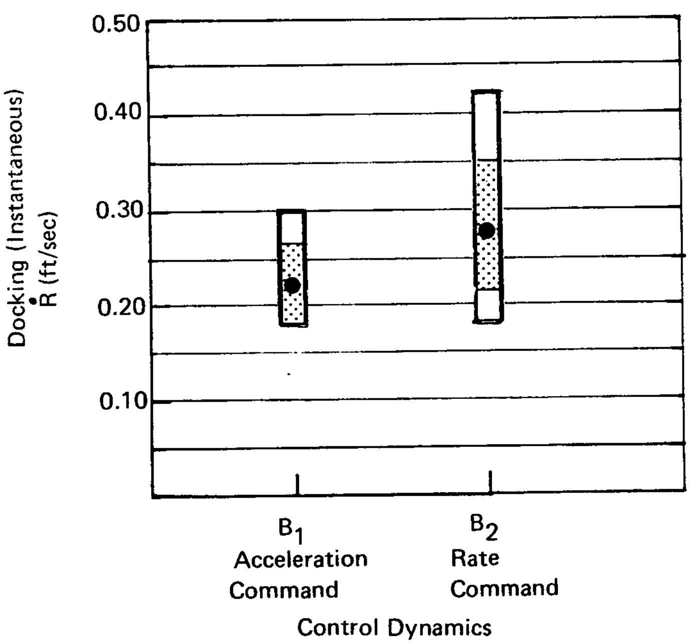


Figure 18. Docking Velocity for Acceleration Command B_1 and Rate Command B_2

4.2.3 Effects of Docking Aids

Only one measure responded significantly to changing docking aids (C) from gunsight (C_1) to reticle (C_2). This was the instantaneous docking velocity ($\dot{R}$) shown in Figure 19. Docking rates tended to be higher with the reticle than with the gunsight. This is due to the reduced alignment information available with the reticle, leading to less precise docking alignment control and hence poorer control of docking rates.

The interactive effect (A x C) of Displays and Docking Aids on probe positioning at docking (y) is shown in Figure 20. This shows that with the reticle (C_2) the use of R and $\dot{R}$ displays (A_1) gives higher errors than without them; while with the gunsight (C_1) the errors are lower with R and $\dot{R}$ displays.

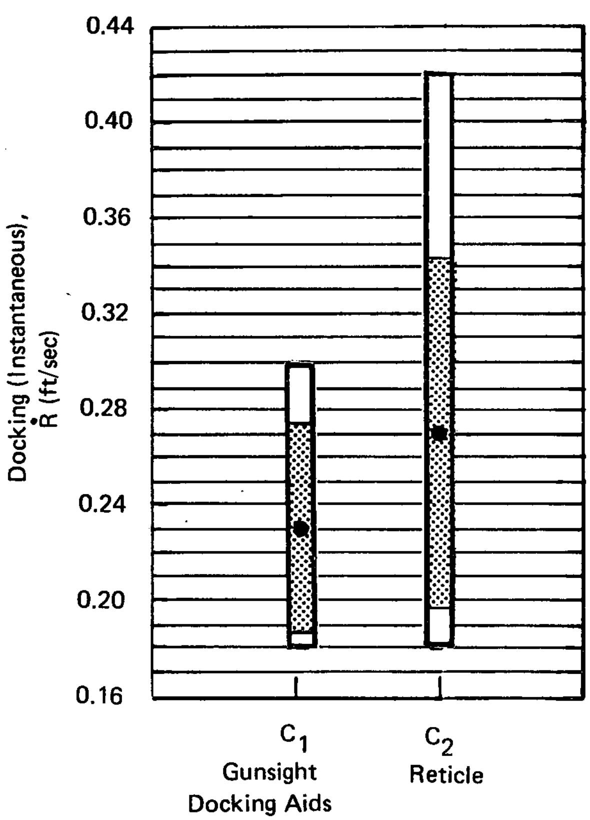


Figure 19. Effect of Docking Aids on Docking Velocity

Note: The plotted points are joined by lines to indicate directionality, not continuity.

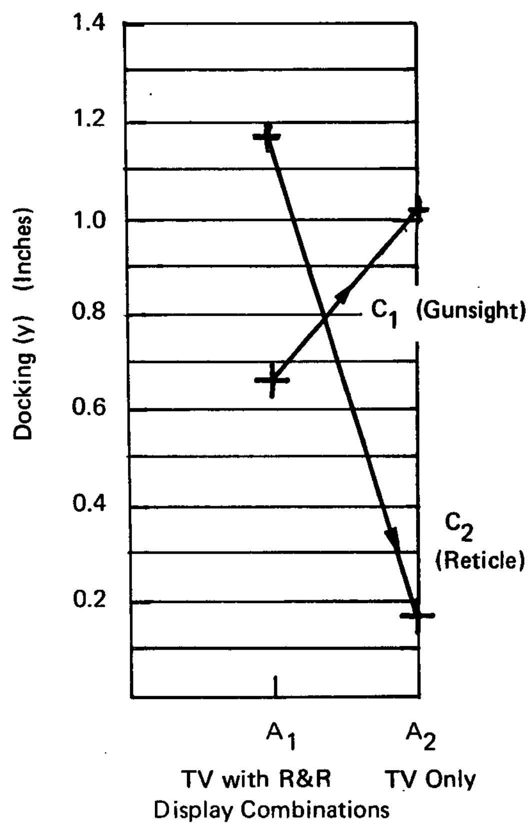


Figure 20. Significant Interactions Between Display Combinations and Docking Aids

The errors at docking viewed across displays were created by a combination of operator technique, work load and available information. When using the gunsight adding R and $\dot{R}$ (A_2) readouts increased the available information to the operator forcing him to control these parameters with resulting diversion of attention, degrading the accuracy of docking. When R and $\dot{R}$ were not displayed (A_1) the operator was able to devote added concentration to the task of controlling Y only.

When the reticle was used as the primary display a specific point on the task board was used for docking which did not provide range cues on the monitor. The operator was then forced to rely upon the R and $\dot{R}$ (A_2) readouts during docking. When $\dot{R}$ was controlled properly additional time was available to concentrate on Y. However, when R and $\dot{R}$ information was not displayed (A_1) the operator was not adequately aware of his position or closure rate and the control activity increased with resulting errors in Y at docking.

4.2.4 Multiple Correlation Analysis

In the multiple correlation analysis of the 16 dependent variables measured during the maneuvering experiment shown in Table XIV, very few significant correlations were found, indicating that there is considerable independence among these various measures.

There were twelve significant correlations, only those greater than 0.5 are now discussed. These are:

- Propellant expenditure and total time of flight
- Mean translation rate and peak translation rate
- Docking velocity and mean yawing error
- Roll error during translation and roll error at docking

There was a high correlation (0.7834) between fuel expenditure and total time. This was expected, since for constant-velocity, translational maneuvers the longer the trial the more fuel is consumed for attitude control.

The high correlation (0.6627) between mean translation rate ($\dot{R}$) and peak translation rate ($\dot{R}_{PEAK}$) is also to be expected. High rates tend to persist and inflate the mean rate.

The negative correlation (-0.5177) between rate at docking ($\dot{R}$) and mean yawing error during translation (ϵ_y) indicates that as docking rates go up, errors in yaw go down. This is attributed to drift rates induced by rises or depressions on the precision floor. Even with the high degree of flatness specified 0.002 inch is sufficient to induce yawing errors at very low rates.

The final correlation to be considered is (0.6264) between roll errors during translation and roll error at docking. This is attributed to failure to take out errors during translation which are likely to produce docking errors. This failure to take out rolling error is probably due to its relative unimportance during the crucial docking maneuver, since the docking mechanism allows docking errors in roll up to ±20°.

4.3 CONCLUSIONS

4.3.1 Manipulation Experiments

In addition to a number of specific conclusions which may be drawn from the data and which will be discussed below and also in Section 4.4 Hardware Implications and 6.0 Recommendations for Further Research, a general but fundamentally important conclusion can be reached. In a high fidelity simulation of a wide range of in-space maintenance and servicing operations, the operator was, with minimal training, able to perform all of the tasks assigned with a great majority of the equipment combinations. The specific findings discussed in Section 4.0 relate to the different levels of successful performance insofar as these were determined by the experimental variation of the system parameters, displays and controls. These findings are now summarized into some definite conclusions.

TABLE XIV
MULTIPLE CORRELATION MATRIX FOR ALL DEPENDENT VARIABLES USED IN THE MANEUVERING EXPERIMENT

```
.0076 rax is in control, sign on.
Mid anov 073583818450500
M.0073  ACTION IN PROGRESS
TODAYS DATE IS 02/07/72
M.0072  BEGIN
/input
/include stat
/endrun
```



```
IS A CORRELATION ANALYSIS DESIRED.(YES OR NO)
yes
INPUT THE NUMBER OF VARIABLES(M.LE.20) AND THE NO.OF OBSERVATIONS(N.LE.60).(M,N)

16,24

INPUT THE  24 OBSERVATIONS FOR EACH OF THE  16 VARIABLES.ONE SET OF OBSERVATIONS PER LINE
```



```
41.,44.,42.,27.,46.,39.,36.,45.,25.,23.,45.,27.,33.,27.,32.,51.,41.,27.,48.,
33.,37.,25.,39.,31.,
7.,11.,6.,11.,8.,10.,6.,12.,4.,10.,6.,8.,5.,7.,5.,20.,6.,6.,7.,9.,7.,8.,5.,8.,
.22,.26,.26,.28,.17,.29,.27,.26,.32,.27,.33,.27,.32,.36,.34,.42,.37,.35,.18,
.38,.29,.29,.2,.24,
.45,.42,.6,.48,.42,.48,.42,.42,.45,.42,.48,.54,.48,.51,.66,.63,.54,.42,.39,.66,
.48,.45,.39,.42,
2.8,2.3,10.,1.4,5.9,7.2,10.,6.3,5.,6.3,11.,8.1,10.,7.7,7.,9.5,2.2,6.3,2.4,9.9,
4.,6.8,6.,6.3,
4.8,.6,.9,.2,3.7,1.2,3.2,1.1,2.5,.7,2.8,.9,2.8,1.,3.3,.2,2.2,.8,1.6,2.4,4.5,
0.,4.1,.8,
.4,1.6,2.5,3.8,.8,4.,.6,1.8,.4,4.9,.4,.7,4.5,.4,.4,2.9,1.6,.3,1.4,.6,.8,.5,
.2,1.1,
1.5,.6,1.1,1.4,1.2,.9,2.1,1.1,1.2,.8,.3,1.5,2.1,1.,1.1,.2,.7,2.8,.6,1.1,.3,
2.1,.8,.4,
.56,.43,.9,1.86,.32,1.65,.97,.37,.49,1.35,.82,1.23,.9,0.,1.65,2.2,1.5,1.57,
.75,.82,.82,1.42,1.97,.97,
1.86,1.5,.9,.75,.75,1.87,1.5,.15,.32,.82,1.65,.68,.75,.52,3.41,1.2,3.,1.95,.37,
2.25,.62,.38,.9,1.95,
.18,.3,.3,.21,.21,.3,.21,.3,.21,.21,.24,.24,.24,.27,.18,.42,.24,.18,.24,.3,
.18,.24,.24,.39,
1.,1.,1.5,1.,1.,1.,1.,1.,1.,0.,0.,0.,1.,1.,1.,.5,2.,1.,0.,.5,0.,0.,1.,.5,
3.,5.,3.,10.,10.,5.,2.,1.,0.,3.,5.,2.,6.,3.,0.,0.,5.,3.,5.,5.,3.,7.,1.,3.,
4.,2.,4.,2.,1.,12.,0.,5.,2.,6.,5.,5.,20.,3.,1.,16.,8.,2.,6.,6.,5.,0.,4.,4.,
2.,0.,2.,0.,0.,0.,1.,2.,2.,0.,2.,0.,1.,0.,0.,0.,1.,2.,0.,0.,1.,1.,1.,0.,
302.,280.,284.,240.,320.,242.,284.,298.,215.,209.,270.,252.,247.,220.,244.,
302.,273.,233.,273.,194.,234.,219.,255.,247.,
```

CORRELATION COEFFICIENT MATRIX : MANEUVERING EXPERIMENT

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1.0000															
2	0.3379	1.0000														
3	-0.1984	0.2340	1.0000													
4	0.0230	0.2017	0.6627***	1.0000												
5	-0.0173	0.0106	0.3659	0.4022*	1.0000											
6	0.2324	-0.5144**	-0.2523	-0.0660	-0.0376	1.0000										
7	-0.0126	0.4125*	0.0608	0.0288	0.0140	-0.3970*	1.0000									
8	-0.4338	-0.3391	0.0152	-0.1558	0.1431	-0.0454	-0.0826	1.0000								
9	-0.0942	0.2819	0.2700	0.2525	0.0306	-0.2185	[illegible]	0.0342	1.0000							
10	0.0667	-0.1294	0.3722	0.4497*	0.0219	0.2008	-0.1524	-0.0524	0.3152	1.0000						
11	0.3488	0.6412	0.2207	0.2522	0.3019	-0.5177**	[illegible]	[illegible]*	0.0055	-0.0060	1.0000					
12	0.1523	-0.1340	0.1100	0.1270	-0.1633	0.1140	0.0562	0.1913	-0.0079	[illegible]	[illegible]	1.0000				
13	0.0134	-0.0048	-0.2566	-0.2008	-0.2522	-0.1095	[illegible]	[illegible]	[illegible]	-0.1132	[illegible]	0.0	1.0000			
14	0.2767	0.3453	0.3450	0.2509	0.2864	-0.0673	[illegible]***	[illegible]	[illegible]	[illegible]	[illegible]*	0.0127	-0.0440	1.0000		
15	0.0802	-0.3362*	0.0122	-0.1932	0.1088	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.2545	[illegible]	1.0000	
16	0.7834***	0.2957	-0.3577	-0.2154	-0.1466	0.2426	-0.0771	-0.1575	-0.1114	[illegible]	[illegible]	[illegible]	[illegible]	0.0896	[illegible]	1.0000

1. % Energy Expenditure Fuel
2. % Energy Expenditure Battery
3. Translation ($\dot{R}$) ft/sec
4. Translation ($\dot{R}_{PEAK}$) ft/sec
5. Translation ($\bar{E}_P$) (Deg)
6. Translation ($\bar{E}_Y$) (Deg)
7. Translation ($\bar{E}_R$) (Deg)
8. Translation ($\bar{Y}$) (ft)
9. $\bar{E}$ Range Circumnavigation
10. $\bar{E}$ Range Inspection
11. Docking (Instantaneous) $\dot{R}$ ft/sec
12. Docking (Instantaneous) ($\dot{E}_P$) Deg
13. Docking (Instantaneous) (E_Y) Deg
14. Docking (Instantaneous) (E_R) Deg
15. Docking (Instantaneous) (y)
16. Total Time

LEGEND

*	= $a \leq 0.05$
**	= $a \leq 0.01$
***	= $a \leq 0.001$

1. A single camera, normal to the task board, provided sufficient cues to permit successful completion of all experiments.

2. In E5 Fluid Coupling, workload is increased to the point where the task has to be abandoned when a single display was used but did not present a view normal to the task. This happens where xy alignments are required but information in x or y is not presented via the display because of its camera position.

3. In only 2 of the 5 experiments was there a reduction in mental workload by providing a second display.

4. The only situations where a second display reduced errors was in the case where xy alignment was required but the single camera did not yield information in both axes. (E4 Antenna Installation.)

5. In the special situations where a second display is helpful, there is no clear-cut evidence in favor of either the 45° (A2) or 90° (A3) location. This seems to depend entirely on the task.

6. The use of mirror, tilted at 45° to the task and in the field of view of a single normal camera, in the one case where it was tried, (E5 Fluid Coupling) produced significant reductions in task completion time and workload, over the single display with no mirror.

7. The three controls evaluated impose significantly different physical workloads. The master-controller being the most demanding and the switch controller the least demanding.

8. Significant differences in mental workload across the three controls are indicated by the data, the switch controller being the most demanding and the master controller the least.

9. The tasks evaluated took significantly less time to perform with the master controller system than with the control sticks, which in turn yielded speedier performance than the switch controller.

4.3.2 Maneuvering Experiment

1. Although the analysis of variance failed to yeild any significant results for displays, subjective ratings and the presence of significant interactions involving displays indicated the importance of supplemental R and $\dot{R}$ information, to avoid occassional excessive docking rates.

2. Docking rates tended to be higher than desirable with the reticle than with the gunsight docking aids.

3. Neither of control dynamics investigated (Acceleration Command and Rate Command) in any way influence TV resolution or caused smear during inspection maneuvers.

4. Multiple correlation analysis showed that there was considerable indpendence among the chosen parameters.

5. There was no significant variation in fuel expenditure as a function of control dynamics. Electrical energy expenditure was significantly higher for the rate system.

4.4 HARDWARE IMPLICATIONS

The performance of any system with man in the loop, can be evaluated by considering three basic factors:

(1) Time required to accomplish a task,

(2) The accuracy with which the task was performed, and

(3) Workload imposed in minimizing time and maximizing accuracy.

These measures of performance were used as the basis for evaluating the experiment results. While the configuration of the equipment subjected to evaluation was held constant across all experiments, several hardware deficiencies producing erratic equipment behavior, were noted under certain conditions. Some of these deficiencies were corrected before we began the experimental runs. Others, too extensive to undetake and outside the scope of this program, are documented herein only to establish the actual as opposed to the designed characteristics of the equipment used in the experiment program.

4.4.1 Controllers

4.4.1.1 Anthropomorphic Exoskeleton (Master Controller)

The basic problems encountered in the use of this controller were: operator fatigue, poor operator-controller coupling, high breakout forces and inadvertent motion.

(a) Fatigue

It became readily apparent in the pretraining qualification trials, that fatigue would present a significant problem during performance of any task using the Master Controller. Retention of the operator's arms with the controllers in positions other than straight down even for very short periods of time, fatigued the operator to the point where he could not achieve the level of consistency needed to meet training criteria. To minimize the fatigue problem and to make evaluation of this controller possible, the counterbalancing arrangement shown in Figure 21 was devised and installed on the Master Controller. This crude, but effective arrangement, consisted of an overhead pulley support with counterbalancing weights extending behind the operator. The counterbalance was sufficient to support the controller and the operator's arm in the neutral position. The vertical tubular structure swivels to follow shoulder yaw movements of the controller.

(b) Operator-Controller Coupling

The second problem encountered in the use of this controller was the inability of the operator to execute small commands. This was attributed to poor coupling between the operator's arm and the various controller linkages. Coupling characteristics were significantly improved with installation of contoured rubber pads between the controller linkages and the operator's arm and by firmly strapping the controller to the operator with Velcro binders.

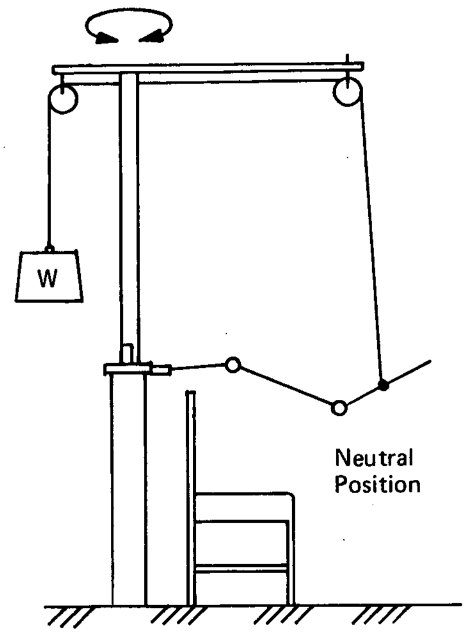


Figure 21. Counterbalance for Master Controller

(c) Break-Out Forces

Due to improper bearing tolerances, breakout forces in wrist and elbow roll tended to be somewhat high and random.

(d) Inadvertent Movement

It was found that in two-handed operations it is difficult to remember to hold the hand not in use, perfectly still. A disengagement switch allowing movement of the master, without movement of the slave is a desirable addition. This feature should be combined with an audio signal which develops a null when the master controller position corresponds exactly to that of the slave manipulation arm.

4.4.1.2 Switch Controller

Some basic modifications to this controller (rearranging of switches) were made after a cursory examination of its layout. Since these modifications were incorporated before the initiation of the experiment program, their descriptions appear in Section 6.0 of Appendix B.

(a) Directional Correlation

The most profound problem encountered in the operation of this controller was the loss of directional correlation between controller and manipulator, following a command for shoulder roll or wrist roll. Any significant angular displacement in shoulder roll disorients all subsequent joints on the manipulator. The elbow pitch switch, for example, after a 90° displacement in shoulder roll, commands the elbow in the yaw plane as does a command for wrist pitch, while the toggles for elbow and wrist-pitch commands, still deflect in the fore-aft direction. The difficulty for manipulator control is compounded at intermediate locations of shoulder and wrist roll. In such situations the only possible way to issue a command is to "feel" the direction resulting from a control input of arbitrary direction, verify it through the display and either follow through if correctly issued or reverse its direction if incorrect. This was quite evident for positions of shoulder roll other than the null position. However, when operating in close quarters where precise motions are mandatory to prevent damage to the work site this approach can not be tolerated.

(b) Breakout Forces

Breakout forces of switches were excessively high and not consistent across all toggles. Use of bidirectional switches which operate with low breakout forces and combine all functions of a single manipulator joint are recommended for future evaluations of a switch controller.

(c) Switch Coordination

Smooth translational motions of the tip (hand) of the manipulator are not possible with the switch controller. Because any one switch can only command rotation of a particular member of the manipulator, at least two switches must be operated simultaneously to produce linear motion. Furthermore, since the angular rates of various joints and lengths of the manipulator linkages are not equal, the commands must be continuously interrupted. The resulting motion is not smooth translation but a jagged trace controlled by a pseudo pulse-width modulation whose duty cycle is developed by extensive operator training.

(d) Rate Variation

Compounding the difficulty of commanding linear motions is the susceptibility of the manipulator to the gravitational field. Depending on the orientation of the manipulator arm, the ratio of pulses required to produce a downward linear motion, differs considerably from that required to produce an upward linear motion, with many variations at intermediate positions.

(e) Residual Forces

The criticism applies to all control systems evaluated, but was worst of all in the levers (control sticks). Because of the lack of force feedback, there were many situations in gripping, connecting, disconnecting, etc., where residual forces were left in the object being manipulated, causing the manipulator arms to frequently slip and hit adjacent objects . Displays, showing forces being exerted in every axis of control would provide useful information.

4.4.1.3 Levers

It had initially appeared that the lever or "joystick" might represent the ideal controller for the anthropormorphic manipulator because it is capable of producing pure translational motions and uncouples positional control of the manipulator tip from the angular position of the intermediate joints. For example, the manipulator tip or jaw can be readily commanded in pure translation, anywhere within the reach envelope, regardless of the shoulder roll or wrist roll position. Further, it provided a position command system for linear motions, and a commandable rate for rotational motions. In other words, it possessed all the attributes of an ideal controller for the 12-M manipulator. Poor hardware implementation of this basically "good" idea was primarily the reason for its poor rating. Some of the problems encountered during its evaluation are described below.

(a) Anthropometry

The anthropometric layout of the lever controllers was extremely poor, and caused fatigue. This was primarily due to incorrect relationships between the control grips – they were too far apart and provided no arm rest. This tended, (with their extreme sensitivity) to lead to single operation (never two at a time) with the spare hand used as a rest for the working hand.

(b) Friction

Breakout forces for commanding Z translation were excessive. This problem was again one of design implementation. High breakout forces were introduced by the negator springs whose sole function was to counterbalance the control handle. Verticial commands invariably resulted in overshoots because of this controller characteristic.

(c) Control Reversals

The most objectionable characteristic of this controller was its frequent injection of control reversals. A control reversal is the displacement of the manipulator arm in a direction which is contrary to that commanded, i.e., a downward motion of the arm in response to an upward command. These control reversals, occur only under certain combinations of adverse conditions; for example, when the commanded rate on any one of the three joints used to provide translation (shoulder pitch, shoulder yaw, and elbow) exceeded the capability of the motor (and gear drive) to develop this rate. A two-dimensional presentation of the resulting motion is illustrated in Figure 22.

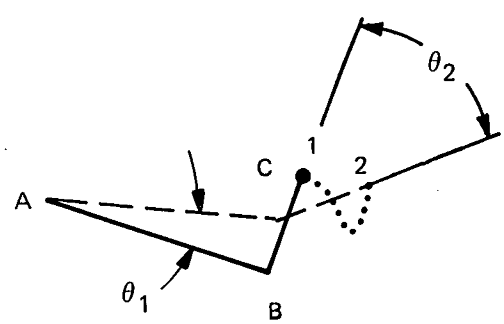


Figure 22. Two Dimensional Illustration of Control Reversal

Translation of Point C, representing the jaw of the manipulator from position 1 to 2, is affected by a counterclockwise rotation of member AB through an angular displacement θ_1 and a clockwise rotation of member BC through an angular displacement θ_2. The angular rates commanded to these members are established by corresponding members in their analog counterpart located within the controller.

If the commanded angular rate for member AB can not be developed by the motor at Joint A, primarily because it is working against gravity, yet member BC working with gravitational force does develop the commanded rate, the immediate motion of point C is downward, followed by a slower upward motion. The path shown in dashed lines in Figure 22 results, rather than the direct horizontal translation commanded by the controller.

Because the control system commands position, the manipulator does eventually achieve the commanded position; however, depending on the orientation of its linkages relative to the gravitational field, the path traced by the manipulator is not predictable.

Indeterminate path motion such as produced by the lever controller, increases the number of errors committed in the execution of a task increases mental and physical workoad, lowering the desirability of such controllers.

(d) Rate Control Switches

Some of the control functions of the levers were implemented by control switches mounted on the top of the hand grip. The breakout forces of the wrist pitch and roll switches were unacceptably high, yielding many inadvertent inputs into the position command part of the system due to physical cross coupling. The other switches tended to be outside the orbit of the digits with the hand properly gripping the handle.

4.4.2 Displays

No significant difficulties were encountered with the video displays or associated equipment used in the experiment program.

One objectionable characteristic of the displays, particularly evident in the primary system (high resolution system) was smear of the image caused by phosphor persistence. Persistence was most pronounced when the camera was panned to follow the manipulator. The smear produced by persistence on the screen was occasionally sufficient to warrant stopping the camera pan operation. Some smear was also evident when highly reflecting surfaces on the manipulator hand moved at relatively high rates across the screen. The latter, however, was infrequent, so its presence was tolerated.

4.4.3 The Optimal Control-Display Combination

As previously observed, any of the system combinations evaluated worked in the sense that the tasks were successfully performed. The question remaining is which one is best for the space applications.

First let's consider displays. In certain instances a second display improves performance, but the improvement is usually small when the single camera is one viewing normal to the task. It could be, that for space applications, the increased weight and data-link of adding further displays and cameras would be unjustified by the performence increment expected. The remarkable success of making two displays out of one by using a mirror should certainly be further investigated since it is not only lighter, but the limited data gathered on it shows it to yield superior performance.

The single normal camera in conjunction with a mirror, probably represents the optimal display system evaluated in this study when weight-space and spacecraft integration factors are considered.

The control system which looks best from the performance viewpoint is the master controller. It rated best on all parameters but physical workload, and electrical energy expenditure as monitored by Integrated Joint Movement Time. In space, because of weightlessness, workload with an exoskeleton would be much reduced, however, energy expenditure should be considered as a factor influencing its selection.

The control sticks rated worst in terms of performance accuracy and mental workload and in the form evaluated would be unacceptable. However, they were such poor examples of the stick type controller that their results should not be generalized to all possible control stick configurations. The switch controller is the second choice. The greater advantages that the switch controller has over the exoskeleton are its: Low weight, Small size, and Simplicity. For these reasons it would be hard to state that the exoskeleton would be the best in-space system.

An ideal controller would be none of the three evaluated but would be something with the weight, size and simplicity characteristics of the switch controller, plus the desirable position control system of the exoskeleton. In the section that follows a system replacing switches with potentiometers is proposed as likely to approximate the "ideal" controller for space use.

5.0 RECOMMENDATIONS ON SPACECRAFT DESIGN FOR SERVICING BY TELEOPERATORS

The five manipulation experiments conducted in this program heavily reinforce the premise that a strong interaction exists between the design of the spacecraft and the manipulator that is required to service and maintain it. Manipulators are of limited use on spacecraft now orbiting the earth, mainly because (1) no provisions exist on these spacecraft which would make their subsystems accessible to a teleoperator and (2) the equipment is not installed or fastened with hardware which could be handled with manipulators.

It should also be noted that assessing the ability of a manipulator to perform a specified task from drawings, specifications or other related documentation is extremely difficult. In the present study, even with the manipulators available to the task designer, the final configuration of a task evolved through an iterative process requires extremely close coordination. It was not until the pretaining qualification runs were made that the feasibility of performing a task in its "as-designed" configuration could be verified. More often than not, either the task or the procedure was modified to facilitate its accomplishment.

Part of this iterative process was by intent. In the effort to establish the limitations of the equipment in performing realistic tasks, few deviations from conventional design approaches were initially considered. Aside from the obviously impossible to perform tasks, i.e., welding, metal cutting, rivetting and bolt removal and replacement (which should not even be considered for spaceborne operations with current manipulators), the tasks exploited the maximum capability of the manipulator, its controllers and available display information.

Generally, the modifications to the task or procedure were made after the pretraining qualification runs, which were used to determine whether the task could be performed consistently. While these modifications appeared to be minor, they greatly enhanced execution of the task.

The paragraphs which follow identify some design characteristics which should be considered in the design of a spacecraft to permit servicing with general-purpose anthropomorphic manipulators. Manipulator capabilities are assumed to be analogous to those of the 12-M manipulator.

The recommendiations are divided into two categories:

1. General Recommendations for the Design Spacecraft, and
2. Specific guidelines based on the tasks performed in the experiment program.

5.1 GENERAL RECOMMENDATIONS

- Bolts, nuts, screws, etc. should not be used to fasten equipment or replaceable modules. Self-aligning captive pins are recommended substitutes.
- Hinged doors are preferable to completely removable ports.
- All surfaces to be handled by the manipulator jaws should be coated or lined with a thin layer of rubber or similar material to

    (a) Permit flexure to accommodate alignment (See E1, E5)
    (b) Ensure a firm grasp of the module

- Enhancement of contrast between flange on module and the lead-in to the track is desirable.
- Recessed handles are acceptable providing sufficient contrasts exists between the handle and background in the recess.
- Shape of handle (cross section) should assure positive indexing with manipulator jaw. (A square handle was used on the Battery Replacement, E2, to index with the notch in the manipulator jaws. A handle of circular cross section was not sufficient.)
- Thruster replacement should only be considered in the modular mode. This implies grouping the jets into clusters which include valves, plumbing and all internal wiring. The interface between the module and to the spacecraft should minimize the number of fluid and electrical connections.

  A compression type seal using "O" rings or equivalent seal which does not require application of sliding forces to engage or disengage is desirable.

  Self centering, spring loaded contacts on electrical connectors (i.e. ball-cone or similar nonbinding surfaces).

  Module attachment by means of cams to produce compressive forces between parts (i.e., latches on Thruster Replacement, E1). Screws, bolts or other loose fasteners can not be handled with the 12-M or similar manipulators.

- Visual cues for indexing and alignment are extremely important.

  Enhancing edges or perpendicular surfaces on the module to give depth cues, i.e., painting the edges of the cluster parallel to the LOS of the camera yields angular alignment cues; outline of the module on the mating base provides further alignment cues. Both approaches were used in Thruster Replacement, E1, and found extremely helpful.

- A double track arrangement with a 10° lead angle is desirable for initial alignment and installation of a module (battery or film cassette) within a spacecraft compartment.

5.2 SPECIFIC GUIDELINES

- Inspection of spacecraft compartments through small 15-20 cm (6-8 inch) apertures by insertion of a mirror is practical and very effective.
- Compartment illumination is not required. The manipulator can effectively provide the illumination as part of the inspection mirror.
- Inspection of compartments mounted against the skin of the spacecraft within 50-100 cm (~ 20 to 40 inches) of the aperture is feasible - with good resolution. Broken wires, loose terminals and fluid leaks can be readily identified.
- Nesting of circular objects with little or no taper should be avoided. (Alignment of antenna base coaxial connector was the most difficult task encountered in the experiment program.)
- Alignment combined with force application can be accomplished, but should be avoided.
- Depth perception is a necessity for precise alignment operations. The incorporation of spacers seats or cones to aid in alignment tasks should be considered whenever possible.
- Visual aids to give cues when engagement is complete are extremely desirable in the absence of force feedback.
- Engagement and disengagement fluid couplings with self-sealing features are feasible and relatively easy to use. Such couplings may be considered for spacecraft refueling or replenishment of cryogenics.

- Parts requiring precise alignment should be equipped with guides which accommodate

  ±1/2 inch linear misalignment
  ±5 deg. angular misalignment

- Modules should be designed for handling by a single manipulator arm. Two-handed operations should be avoided. Lack of force feedback induces extreme stresses in the manipulator arm and may result in serious damage to the equipment.
- The provision of force indicator gages for each axis of control would minimize errors due to inadvertently applied residual forces.
- Joint position indicators would eliminate the problem of arm position disorientation found with the switch controller.
- Use displays which are similar in size and resolution.
- Provide a disengagement switch for the master-slave exoskeleton to allow movement of the master without moving the slave.

6.0 RECOMMENDATIONS FOR FURTHER INVESTIGATIONS

6.1 DISPLAY INVESTIGATIONS

Results of the experiment program verify that performance of the teleoperator system was somewhat insensitive to variations in displays. Further, it confirmed the importance of a single camera normal to the task board with guides or spacers to assist alignment in depth. Elimination of these guides which simplify the work piece may be possible if the camera used could provide sufficient cues for depth perception.

It is recommended that experiments E4, Antenna Installation, and E5, Fluid Coupling, which represented tasks with severe alignment requirements, be repeated with stereo and stereo-color displays. With all other parameters held constant, the incremental improvement in performance attributable to 3D and color can be isolated.

A further possibility deserving of evaluation is a single TV camera gimballed for panning in pitch and yaw and mounted on an extendable boom. In this way, all views could be obtained using one camera and the results compared with various stereo, color and mirror combinations. Only a full evaluation of such alternatives can lead to realistic tradeoffs.

6.2 DOCKING DYNAMICS

All experiments performed to date have considered the target spacecraft to be stabilized during the docking maneuver. This condition is realistic if the task to be performed by the teleoperator is one of periodic servicing (i.e., refueling, replenishing cryogences for sensors, film cassette replacement, etc.). A more general condition would be docking with a spacecraft which retains some residual spin or tumble rate. Such a condition may arise from a failure in propulsion or in the stabilization control system.

A study is recommended to define the dynamics of docking with spinning or tumbling targets, using a 6 DOF simulator facility and to verify and correlate the results of the analytical effort through simulation; it should constitute the next step of investigation in the maneuvering and docking field.

6.3 MANIPULATORS

Two basic philosophies prevail for service and maintenance of orbiting spacecraft. The first uses a manipulator to make a wide variety of repairs on a marginally prepared spacecraft such as investigated in this effort. In this case, the manipulator would be required to repair existing types of space hardware not specifically geared to the operation of the manipulator, and would probably have to accurately simulate many of the capabilities of the human arm. Development of such manipulators and associated controllers to command precise control is extremely complex and possibly unjustifiable.

The second method uses a spacecraft which is designed to be maintained and serviced by manipulators. Such design approaches have already been investigated for future generations of spacecraft. The modular spacecraft design (Ref. 2) is such an approach. In this case, the manipulator can assume non-anthropomorphic configurations which are simpler, more reliable, easier to control, and their performance can be predicted with a higher degree of confidence.

It is recommended that an effort be undertaken to study and evaluate performance of non-anthropomorphic manipulators to service and maintain modular spacecraft and to demonstrate their versatility through feasibility models. Such a system would have the ability to obtain pure linear motion in all axes, without any requirement for complex control coordination.

One possibility for a special-purpose manipulator is shown in Figure 23 , depicting a typical concept of a teleoperator which could be used to service a modular spacecraft by removing and replacing several modules either completely automatically or with manned intervention. More versatile configurations for performing general functions, i.e., extension of solar arrays, should also be investigated.

6.4 CONTROLLERS

Controllers were responsible for the greatest portion of the experimentally induced variance. The factors affecting performance with the various controllers were previously discussed in preceding sections. The need for an improved controller to be used with anthropomorphic manipulators still exists.

The following characteristics should be considered in any future design effort to produce a controller for multiple degree-of-freedom manipulators.

1. All levers, switches, sticks or potentiometers used to command motion of a manipulator joint should be directionally coupled to the motion of its corresponding manipulator member.

2. The controller should not require the constant attention of the operator to hold the position of the manipulator arms.

3. Provisions should be made to prevent the operator from commanding rates which exceed the rate development capability of the manipulator. A force on the controller, resisting motion, would be sufficient to alert the operator of the fact that the rate he commands cannot be achieved by the manipulator arms.

4. Consideration should be given to minimizing, (a) the size of the controller and (b) the space required to operate it so that its integration into a manned spacecraft could be facilitated.

5. Position command control dynamics with modulation, similar to that used in the master controller, is greatly to be preferred to rate command.

It is recommended that the controller configuration shown conceptually in Figure 24 receive consideration for controlling multiple degree-of-freedom anthopomorphic manipulators.

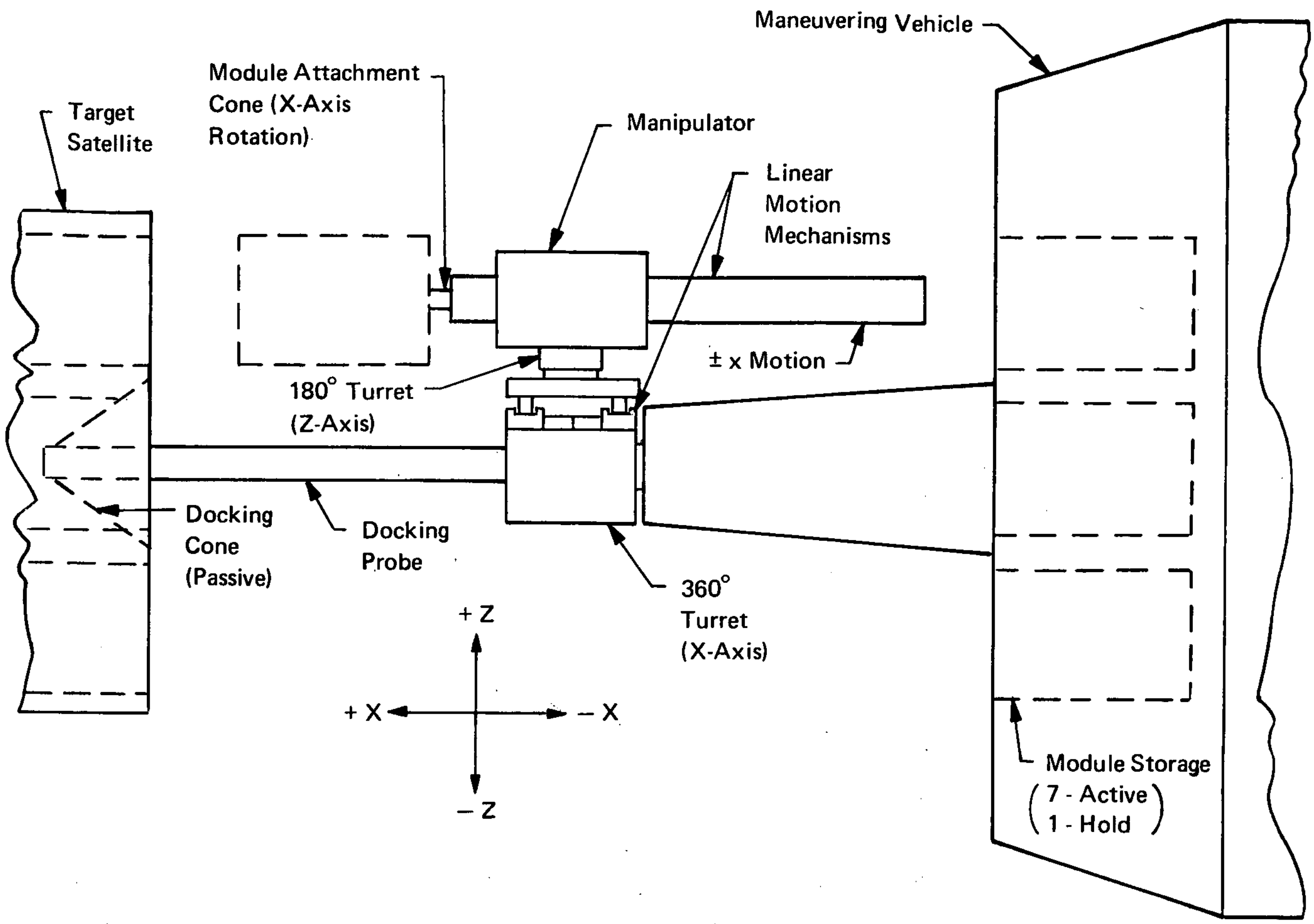


Figure 23. Non-Anthropomorphic Manipulator Concept

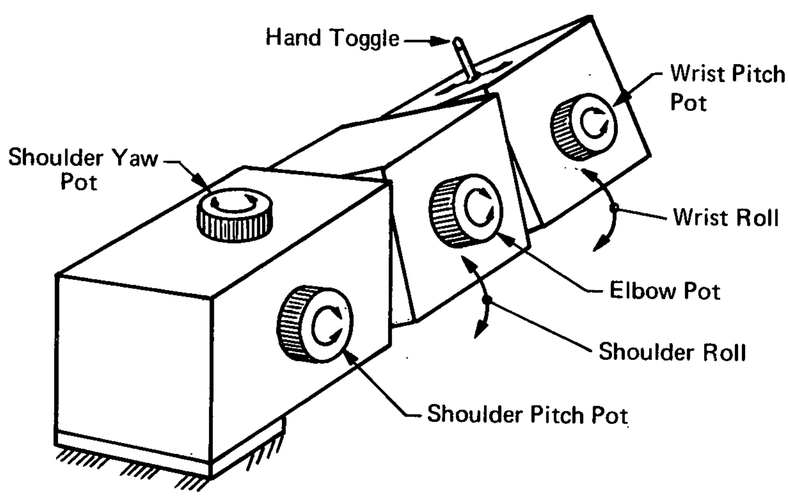


Figure 24. Conceptual Controller for Multiple Degree of Freedom Manipulators

APPENDIX A
DETAILED MANIPULATION EXPERIMENTS

This appendix contains detailed descriptions for each of the five manipulation Experiments E1 through E5 and for Experiment E6, Maneuvering and Docking.

1.0 EXPERIMENT E1 – THRUSTER REPLACEMENT

1.1 OBJECTIVES

- To establish the utility of a teleoperator as an operational device for maintaining and servicing orbiting spacecraft.
- To establish requirements for spacecraft design which will permit in-orbit maintenance and repair using teleoperators.

Specific Elements to be Demonstrated

(a) Engage and disengage cam-action latches

(b) Grasp and remove jet cluster

(c) Orient and engage alignment pins

(d) Two hand coordination in positioning and locking latches

1.2 EXPERIMENTAL APPARATUS

1.2.1 Task Board

The experiment task is to remove and replace a suitably designed cluster of four thruster jets from the task board, which consists of a metallic cone-cylinder configuration representing the exterior surface of a small satellite. A photograph of the cluster is shown in Figure A-1.

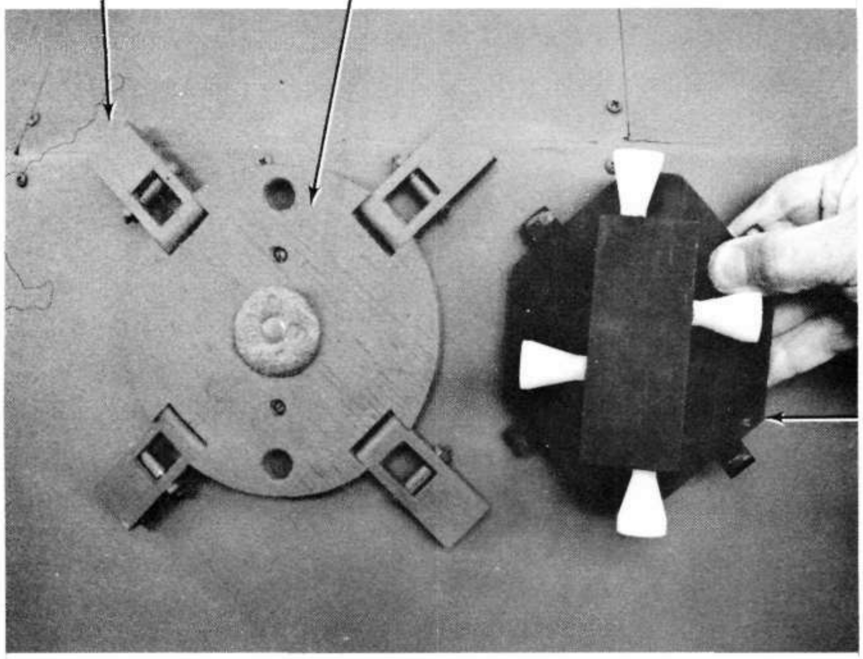


Figure A-1. Cluster of Thruster Jets

The replaceable portion of the cluster contains four jets, associated valves, and internal manifolds. Removal from the spacecraft requires severing the main propellant feed line – represented by a compression type "O" ring seal shown in Figure A-2. This approach would require an in-line self-sealing disconnect (part of the spacecraft at the plane of separation).

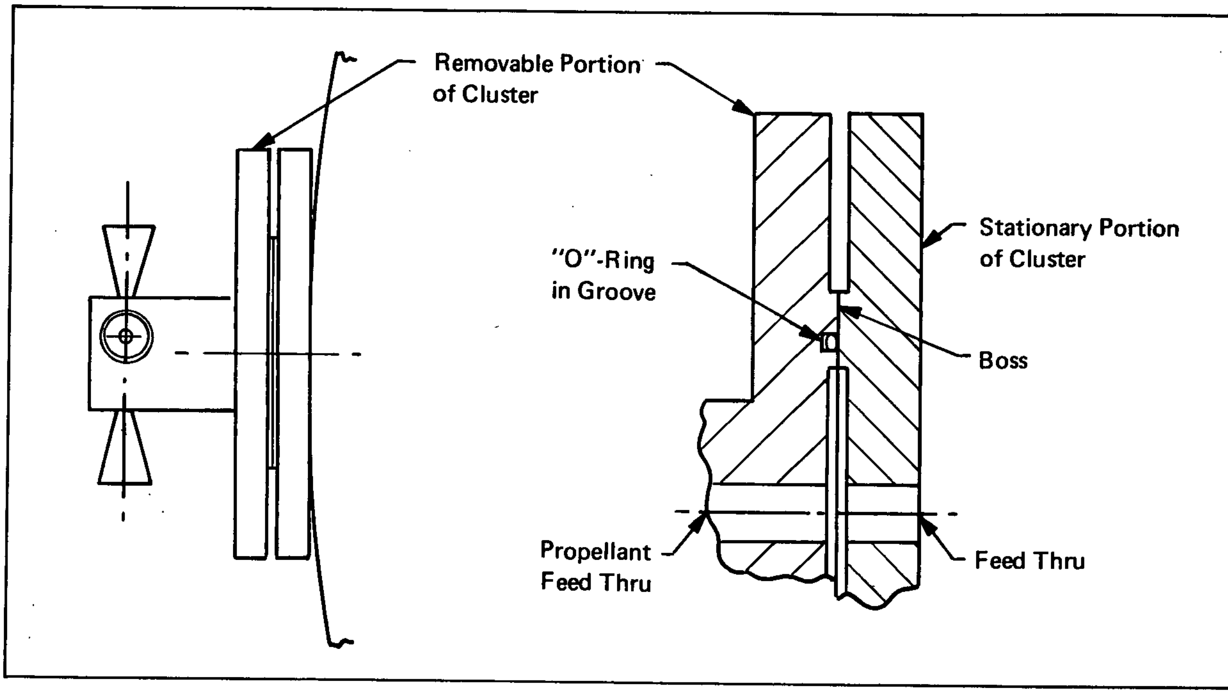


Figure A-2. Propellant Feed Through and Fluid Seal

1.2.2 Displays

The closed circuit TV systems described in Section 7.0, Appendix B, were used exclusively to monitor the task. The number of cameras and camera locations constitute independent variables. Three such combinations were investigated: (Figure A3.)

Condition A1

A single camera, at location X, mounted slightly above and behind the manipulator arms.

Condition A2

Two cameras, one mounted as above and one at 45° to the face of the task board; both cameras at locations X and Y and the task are contained in the same horizontal plane.

Condition A3

Two cameras as above but with the 2nd camera repositioned from 45° to 90°; both cameras at locations X and Z, and the board are contained in the same horizontal plane.

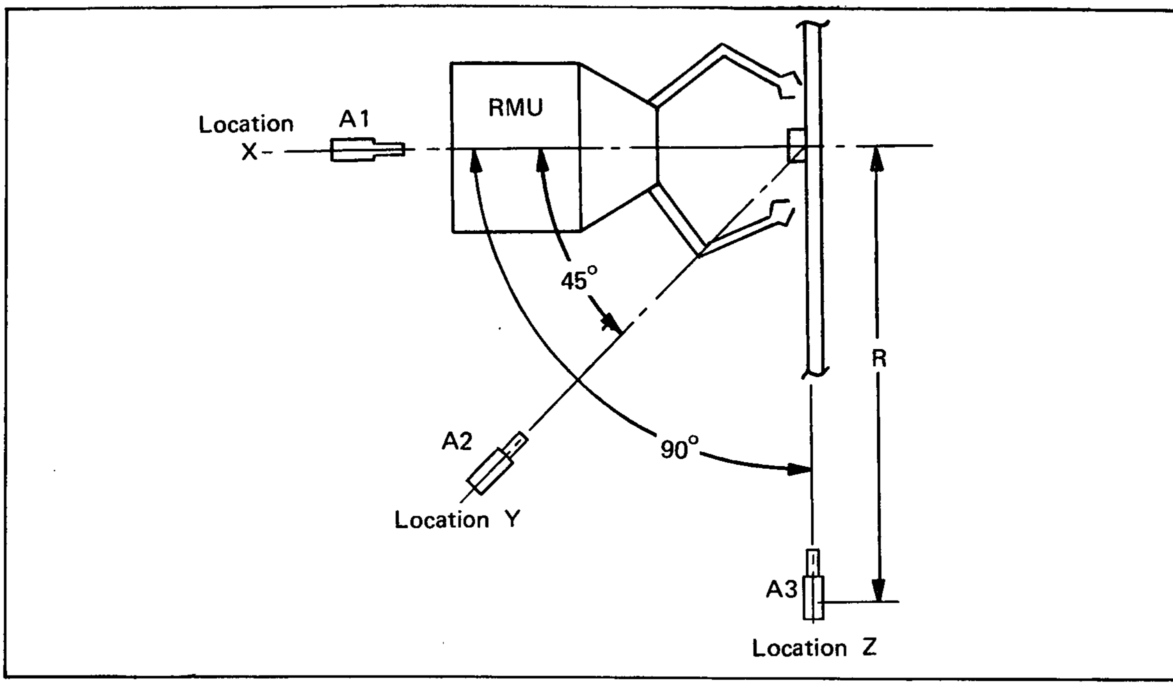


Figure A-3. Camera Locations

Regardless of their angular orientation, all camera locations were equidistant from the task center ((constant R~ 1.84 m) (6 ft)). Characteristics of the equipment used in these arrangements, identified as Primary or Secondary Display Systems, are described in paragraphs 7.1 and 7.2, Appendix B.

1.2.3 Controllers

The three controllers evaluated in this experiment as independent variables include:

Switch Box – Utilizing a "momentary on," "off," "momentary on" switch to command motion to each joint of the manipulator arms.

Master Controller – An exoskeleton anthropomorphic controller which is "worn" by the operator. A motion of a joint in this controller will produce a corresponding motion of the slave manipulator arm.

Lever – This controller also commands position, however the commands are generated by lever displacements in three orthogonal axes, which in turn command position to the tip or jaw of the manipulator arm.

Complete descriptions of the controller's physical and functional characteristics were presented in Section 6.0 of Appendix B.

1.2.4 Illumination

To eliminate the possible influence of illumination on displays, illuminating conditions were very closely controlled. All experiment runs were made using high contrast illumination. This illuminating condition was produced by a single 650-watt spotlight placed at 45° to the task board (adjacent to camera at location Y). The spotlight was at approximately the same height as the task.

1.2.5 Operators

The same test subject (a Bell test pilot) trained to the level of consistency performed all experimental runs involving manipulation. Test subject qualifications appear in Section 7 of this appendix.

1.3 PROCEDURE

The operator was instructed of the task to be performed. "With the initial conditions satisfied, unlatch and remove the cluster of jets, and position it away from the task base, but within field of view. Align cluster with the base on the task board and latch it in position."

1.3.1 Initial Conditions

1. RMU docked to task board base, pad cushion "off"
2. RMU XMTR/RCVR "off"
3. RMU IR Target "off"
4. Task board illuminated by a single high intensity 650-watt spotlight at 45° to the task
5. Operator trial as indicated by the matrix element (R)
6. Controller as indicated by the matrix element (B) — see Table A-1
7. Camera placement as indicated by the matrix element (A)
8. Operator stationed at the manipulator or controller facing away from the task board and commanding operations through cues revealed to him by the visual displays only (one or two TV monitors).
9. Task board frame vertical and 37 cm (15 in.) away from foremost position on track.
10. Operator trained to the level of consistency.
11. Zoom camera (at location X) until the task covers approximately 50% of the area on the monitor.

1.3.2 Initiate Task

Randomly select the combination of variables for the run to be made from Table A-1. If the encircled cell were selected the conditions would be: one camera, switch box controller and the first replication by the operator for these conditions.

TABLE A-1
MATRIX OF EXPERIMENTAL RUNS A(3) x B(3) x R(3)

DISPLAYS	Replications	CONTROLLER TYPES: Switch Controller B_1	Master Controller B_2	Levers B_3
One Camera Normal to Task Board A_1	R_1	$A_1B_1R_1$	$A_1B_2R_1$	$A_1B_3R_1$
	R_2	$A_1B_1R_2$	$A_1B_2R_2$	$A_1B_3R_2$
	R_3	$A_1B_1R_3$	$A_1B_2R_3$	$A_1B_3R_3$
Two Cameras, One Normal and One at 45° to Task in Horizontal Plane A_2	R_1	$A_2B_1R_1$	$A_2B_2R_1$	$A_2B_3R_1$
	R_2	$A_2B_1R_2$	$A_2B_2R_2$	$A_2B_3R_2$
	R_3	$A_2B_1R_3$	$A_2B_2R_3$	$A_2B_3R_3$
Two Cameras, One Normal and One Parallel to Task in Horizontal Plane A_3	R_1	$A_3B_1R_1$	$A_3B_2R_1$	$A_3B_3R_1$
	R_2	$A_3B_1R_2$	$A_3B_2R_2$	$A_3B_3R_2$
	R_3	$A_3B_1R_3$	$A_3B_2R_3$	$A_3B_3R_3$

Subtask 1 – REMOVAL

1. Set teleoperator hands to rest at 3 o'clock and 9 o'clock positions.
2. [START TIMER.] Open latch 1, (Figure A-4) with right hand.
3. Open latch 2 with right hand.
4. Grasp knob with right hand.
5. Open latch 3 with left hand.
6. Open latch 4 with left hand.
7. Remove assembly with right hand.

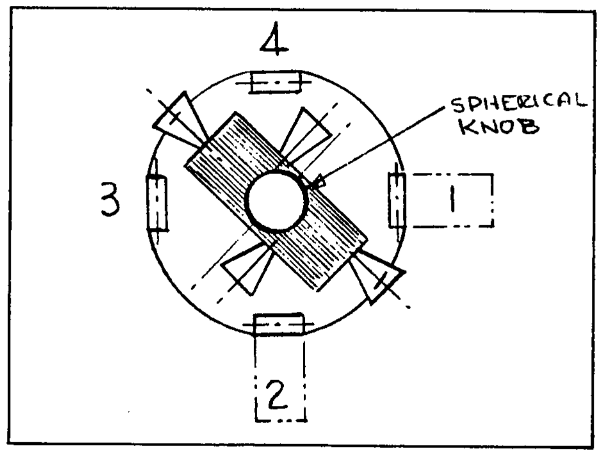


Figure A-4. Latch Identification

[RECORD TIME]

Subtask 2 – INSTALLATION

8. [START TIMER.] Replace assembly with right hand.
9. Apply pressure on knob with left hand. (Ensures proper seating.)
10. Remove right hand from knob.
11. Close latch 1 with right hand.
12. Close latch 2 with right hand.
13. Put pressure on assembly to the right of the knob with right hand.

14. Close latch 3 with left hand.
15. Close latch 4 with left hand.
16. Put left hand in rest position at 9 o'clock.
17. Put right hand in rest position at 3 o'clock. [RECORD TIME.]

1.3.3 Randomly select another element of the matrix for the given pilot and repeat experiment until all elements have been exhausted.

Control of extraneous variables, data recording and data analysis procedures are identical for all experiments and are presented in Section 7.0 of this appendix.

2.0 EXPERIMENT E2 - BATTERY REPLACEMENT

2.1 OBJECTIVE

To evaluate a general purpose mainpulator and associated controllers and displays in performing a typical maintenance task (removal/replacement of a battery pack).

Specific Elements to be Demonstrated

(a) Latch and unlatch one-quarter-turn fasteners.

(b) Open/close a hinged access door.

* (c) Perform a 9 in. translational motion along the fore-aft direction.

(d) Align flanges of a box with the track in the compartment.

(e) Exert sufficient force along the fore and aft direction to overcome sliding friction and to engage two knife type electrical connectors.

2.2 EXPERIMENTAL APPARATUS

2.2.1 Task Board

The experiment task is to remove and replace a mockup of a battery, suitably designed for handling by manipulators.

The battery, shown installed in Figure A-5 is 30.5 x 20.3 x 12.7 cm (12 in. x 8 in. x 5 in.) overall. It is supported in the task board by means of a flange which is 3.18 mm (1/8 in.) thick and extends one inch around the battery pack, dividing equally the 12.7 cm (5in.) dimension. This flange is inserted into a track on the task board. A tapered lead-in is provided in the forward opening of the track to facilitate alignment. Two knife-type slide connectors are incorporated on the far end of the battery box. When the battery box is properly installed and the electrical connection mated, an indicator light on the forward panel is turned on. In addition to this indicator light, the forward panel incorporates a recessed handle. The handle, shown in view AA of Figure A-5 is rectangular ~ 1.52 cm (5/8 in.) square to assure proper indexing when grasped by the manipulator hand. It is covered with a thin layer of rubber to improve its holding characteristics.

The battery pack is designed so it can be removed and/or replaced by either the right or the left hand of the manipulator, while a two hand operation may also be attempted.

Insofar as spacecraft power supplies and other electronic equipment are seldom integrated with the external skin of the spacecraft, a hinged access door has also been included in this task board. This door which must be opened to gain access to the battery pack is secured with one one-quarter-turn flush latch.

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* Translation motion in the fore-aft direction could not be performed – manipulator motions limited. Task Board inclination was changed to 30° vertical

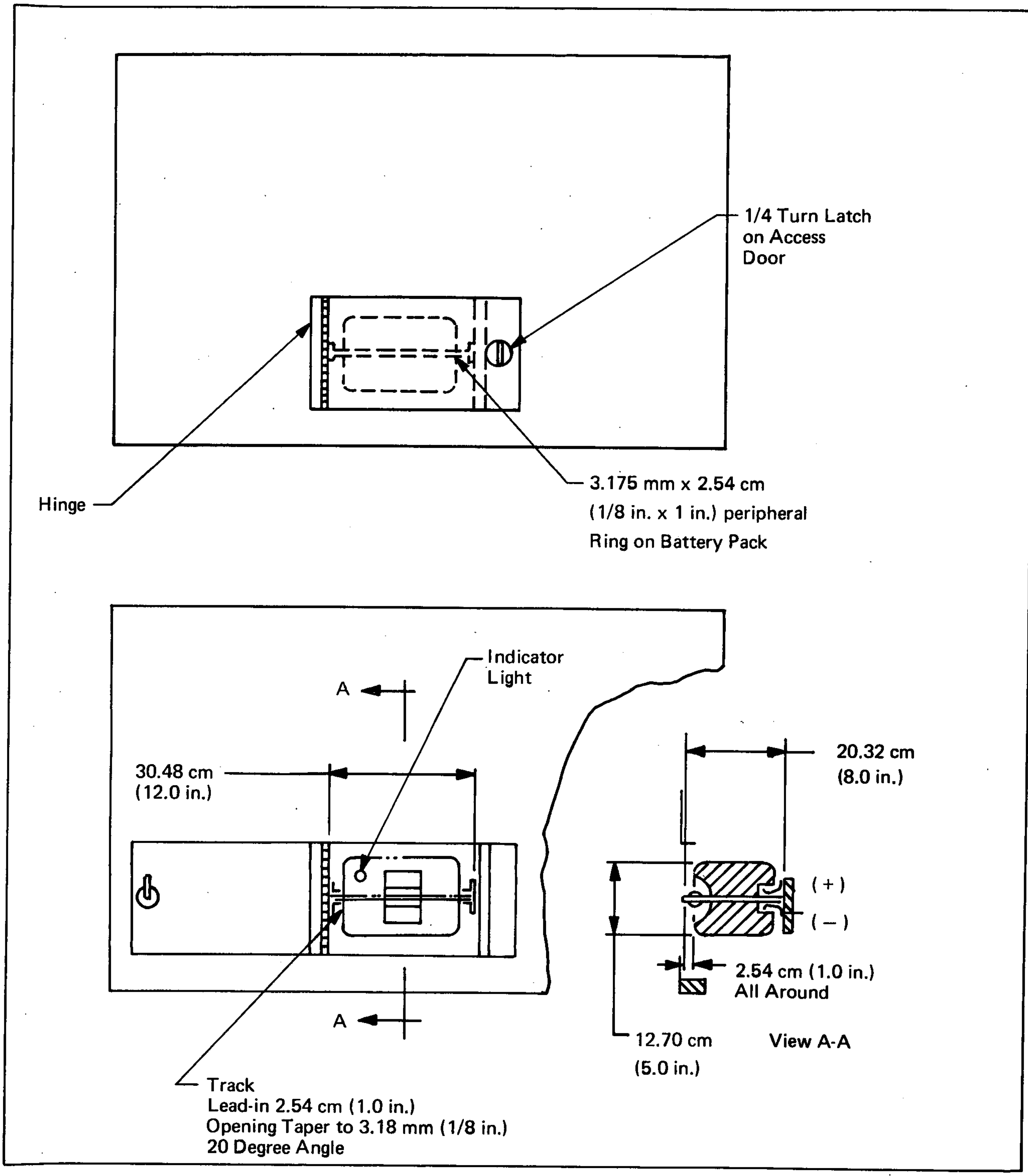

Figure A-5. Details of Task Board

2.2.2 Displays

The three conditions involving the number of cameras and camera location which constitute independent variables are listed below.

Condition A1
A single camera at location X, mounted slightly above and behind the manipulator arms.

Condition A2
Two cameras, one mounted as above and one at 45° to the face of the task board; both cameras at locations X and Y and the task are contained in the same horizontal plane (see Figure A-6).

Condition A3
Two cameras as above but with the 2nd camera repositioned from 45° to 90°; both cameras located at X and Z and the task board contained in the same horizontal plane.

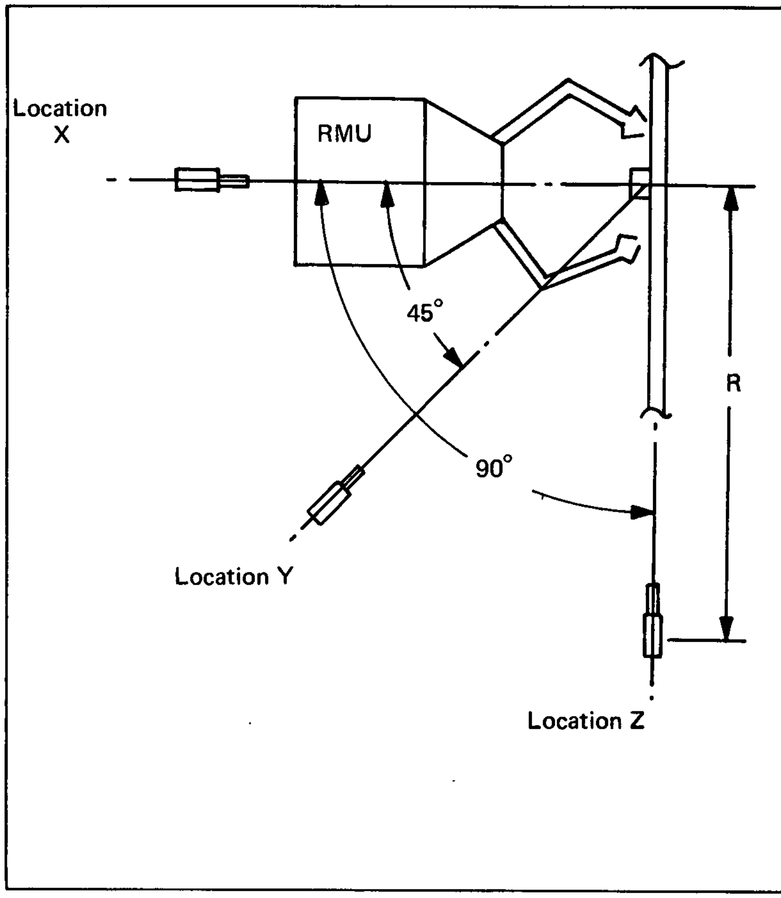

Figure A-6. Camera Locations

Regardless of their angular orientation, all cameras were equidistant from the task center ((Constant R $\approx$ 1.83 m. (6 ft)). Characteristics of the equipment used in these arrangements, identified as Primary or Secondary display systems are described in paragraphs 7.1 and 7.2 of Appendix B.

2.2.3 Controllers

The controllers investigated in this experiment include the Switch Box Master Controller and Levers. Section 6.0 of Appendix B gives complete description of the characteristics of these controllers.

2,2.4 Illumination

All experiment runs were made with high contrast illumination. This illuminating condition was produced by a single spotlight placed at 45° to the task board (adjacent to camera located at Y). The spotlight was at approximately the same height as the task.

2.2.5 Operators

The same test subject (a Bell test pilot) trained to the level of consistency performed all experimental runs involving manipulations. Test subject qualifications appear in Section 7.0 of this appendix.

2.3 PROCEDURE

The operator was instructed of the task to be performed: "With the initial conditions satisfied, unlatch and open hinged access door, remove battery box and place it on the space designated on the task base. Replace battery and close access door."

2.3.1 Initial Conditions

1. RMU docked to task board base, pad cushion "off"
2. RMU XMTR/RCVR "off"
3. RMU IR target "off"
4. Task illuminated by a single, high-intensity 650 watt spotlight at 45° to the task
5. Operator trial as indicated by matrix element (R)
6. Controller as indicated by matrix element (B)
7. Camera placement as indicated by matrix element (A)

(Items 5–7: See Table A-2)

8. Operator stationed at the manipulator controller facing away from the task board and commanding questions through cues revealed to them by the visual displays only (one or two TV monitors)
9. Task board inclined 30° from the vertical toward Teleoperator and ~ 37 cm (~ 15 in.) away from the foremost position on track.
10. Operator trained to the level of consistency
11. Zoom camera (at location X) until both right and left shoulder joints are visible and the door is centered on the monitor.
12. Set teleoperator hands to 3 o'clock and 9 o'clock positions relative to the task and approximately 10 inches away from it.

2.3.2 Initiate Task

Randomly select the combination of variables for the screen to be made from Table A-2

Subtask 1. Removal

1. [START TIMER] - Grasp recessed latch with right hand.

TABLE A-2
A3 x B3 x R3 SUMMARY OF THE EXPERIMENTAL RUNS FOR EXPERIMENT E2
BATTERY REPLACEMENT

DISPLAYS	Replications	CONTROLLER TYPES: Switch Controller B_1	Master Controller B_2	Levers* B_3
One Camera Normal to Task Board A_1	R_1	$A_1B_1R_1$	$A_1B_2R_1$	$A_1B_3R_1$
	R_2	$A_1B_1R_2$	$A_1B_2R_2$	$A_1B_3R_2$
	R_3	$A_1B_1R_3$	$A_1B_2R_3$	$A_1B_3R_3$
Two Cameras, One Normal and One at 45° to Task in Horizontal Plane A_2	R_1	$A_2B_1R_1$	$A_2B_2R_1$	$A_2B_3R_1$
	R_2	$A_2B_1R_2$	$A_2B_2R_2$	$A_2B_3R_2$
	R_3	$A_2B_1R_3$	$A_2B_2R_3$	$A_2B_3R_3$
Two Cameras, One Normal and One Parallel to Task in Horizontal Plane A_3	R_1	$A_3B_1R_2$	$A_3B_2R_1$	$A_3B_3R_1$
	R_2	$A_3B_1R_2$	$A_3B_2R_2$	$A_3B_3R_2$
	R_3	$A_3B_1R_3$	$A_3B_2R_3$	$A_3B_3R_3$

*Condition B_3 could not be fulfilled because of difficulty with the lever controller.

2. Rotate handle 90° ccw using wrist roll.

3. Pull door partially open ~ 20°; release handle.

4. Move right hand between the door and task board and push the door until it is completely open.

5. Grasp battery handle with the right manipulator. Position manipulator hand approximately at the center of the handle.

6. Remove battery box. Pull away from the task board face ~ 30.6 cm (12 inches).

7. Position battery on rack - release handle and move the arm about 15 cm (6 in.) away from the battery. [RECORD TIME]

Subtask 2. Installation

8. [START TIMER] - Align right hand with the battery handle, and grasp it approximately in the center.

9. Remove battery from rack.

10. Insert battery flange into tracks.

11. Push battery until fully installed (indicator light on front panel of box indicates correct positioning of the battery and that the electrical connection is made).

12. Release handle and move right hand to 9 o'clock position.

13. Move left hand (stationed behind the door) and push the door until it is closed.

14. Push against the door with left manipulator (at about the center of door - dark area on door).

15 Grasp handle and rotate at 90° cw with the right manipulator hand.

16. Check to ensure that the latch is engaged (pull on handle).

17. Return manipulators to the 3 and 9 o'clock positions [RECORD TIME]

2.3.3 Randomly select another element of the matrix and repeat experiment until all elements have been exhausted

Control of extraneous variables, data recording, and data analysis procedures are identical for all experiments and are presented in Section 7.0 of this appendix.

3.0 EXPERIMENT E3 - COMPARTMENT INSPECTION

3.1 OBJECTIVE

To evaluate the utility of teleoperators in performing a routine inspection task - within inaccessible* areas.

<u>Specific Elements to be Demonstrated</u>

(a) Removal of inspection port cover.

(b) Ability to perform coarse and fine angular motions of the end effector within confined spaces.

(c) Ability of the operator to detect and identify an induced anomaly within the compartment.

(d) Replacement of inspection port cover.

- Alignment and Orientation
- Fastening

3.2 EXPERIMENTAL APPARATUS

3.2.1 Task Board

The experiment task is to gain access into a compartment of a spacecraft equipped with an inspection port, and to inspect objects which cannot be viewed directly from the outside. To accomplish this, the operator will insert a mirror into the cavity and so orient it, as to display the reflected image of the hidden object(s) to the camera. The compartment will be illuminated. Figure A-7 shows the final configuration of the task board which was used to demonstrate this capability of the teleoperator.

The access port has a 20.3-cm (8-in.) diameter opening. The cover is fastened by means of a suitably designed and spring loaded latch arrangement (Figure A-8) to permit removal and replacement by a single hand operation. Inside the compartment, mounted against the skin of the vehicle, are the objects to be inspected, and visible anomalies identified.

The contents include: (1) a check valve and tubing connections to it, (2) an electrical junction strip with wires attached to all terminals except No. 4; and a "black" box with a cable assembly connector.

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*An area where the entire teleoperator or a boom mounted camera cannot be inserted and maneuvered for the purposes of inspecting its contents.

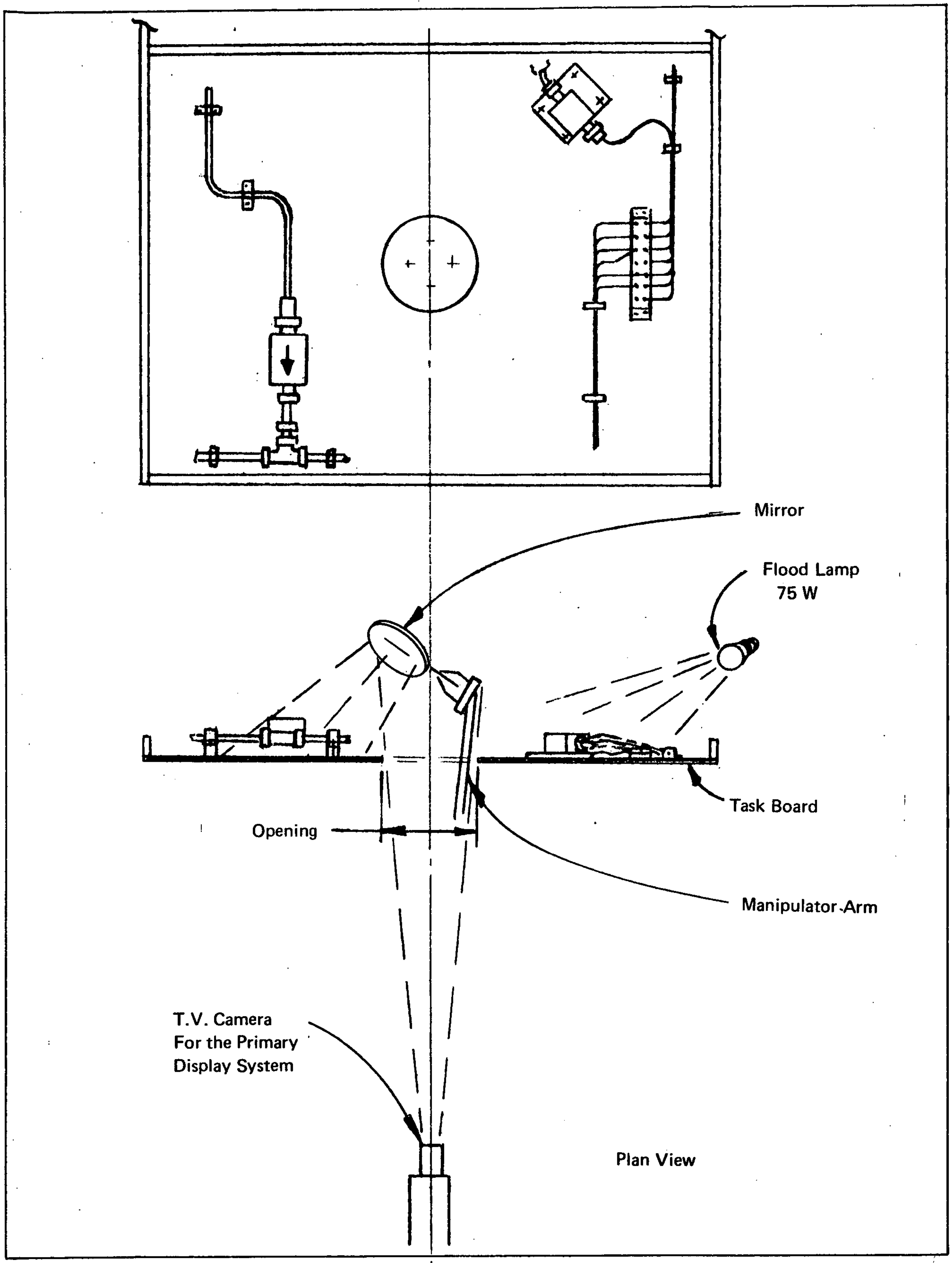

Figure A-7. Task Board for Experiment E3 Compartment Inspection

3.2.2 Displays

The three combinations involving the number of cameras and camera locations which constitute independent variables are listed below. Detailed descriptions of the equipment are found in Section 7.0 of Appendix B.

Condition A1. A single camera at location X mounted slightly above and behind the manipulator arms.

Condition A2. Two cameras, one mounted as above and one at 45° to the face of the task board. Both cameras, at locations X and Y, and the task

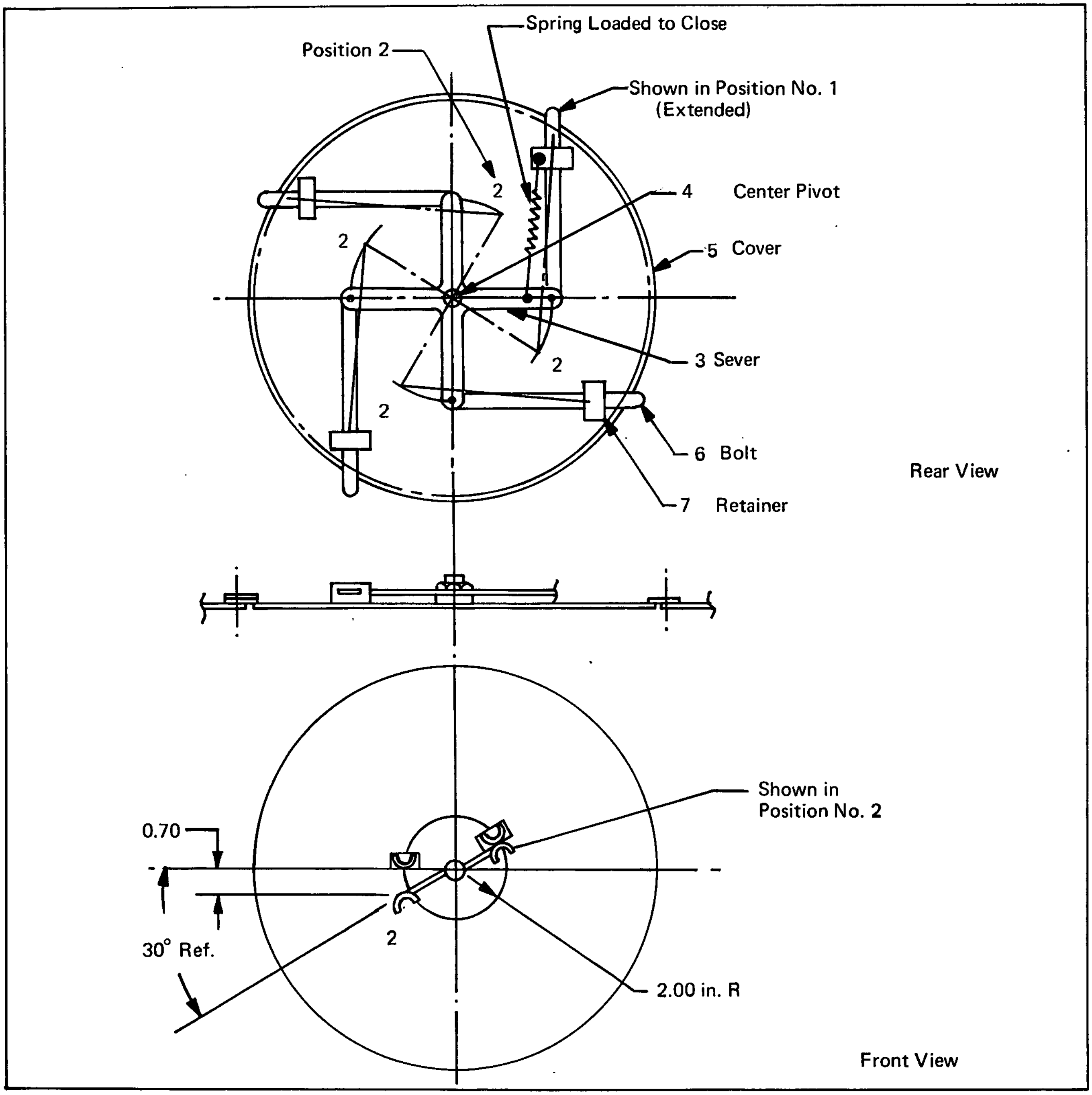

Figure A-8. Access Port Latch

access port on the task board located at the same approximate height. The task board however, will be tilted forward 30°. See Figure A-9.

Condition A3. Two cameras as above but with the second camera repositioned from 45° to 90°. Both cameras located at X and Z, and the access port on the task board are contained in the same horizontal plane.

Regardless of their angular orientation, all cameras were equidistant from the task center (on a 1.83m (6 ft) radius. Characteristics of equipment used in these arrangements identified as primary or secondary display systems are described in paragraphs 7.1 and 7.2 of Appendix B.

3.2.3 Controllers

The controllers to be evaluated in this experiment will include the Switch Box Master Controller and Levers. Section 6.0 of Appendix B gives complete descriptions of the characteristics of these controllers.

3.2.4 Illumination

High contrast illumination produced by a single 650 W spot light was utilized for lighting the front panel. This spot light was positioned adjacent to the camera at location Y (Figure A-9). A separate 75 W flood light was used to illuminate the interior of the compartment.

3.2.5 Operators

The same test subject, (a Bell Test Pilot) trained to a level of consistency performed all experimental runs involving manipulation. The test subject qualifications appear in Section 7.0 of this appendix.

3.2.6 Inspector Mirror

A 12.7-cm (5-inch) diameter plate glass inspection mirror with 20-cm (8-inch) extension stem weighing ~ 227 gm (0.5 lb) was used to inspect the compartment and to identify the condition of its contents.

3.3 PROCEDURE

The operator was instructed of the task to be performed: "Inspect contents of the compartment and identify the presence of broken wires, loose connections or fluid leaks on any components in the immediate vicinity of the access door". The operator was familiar with the contents of the task under normal conditions.

3.3.1 Initial Conditions

1. RMU docked to the task board base pad cushion "off"

2. RMU XMTR/RCVR "off".

3. RMU IR Target "off".

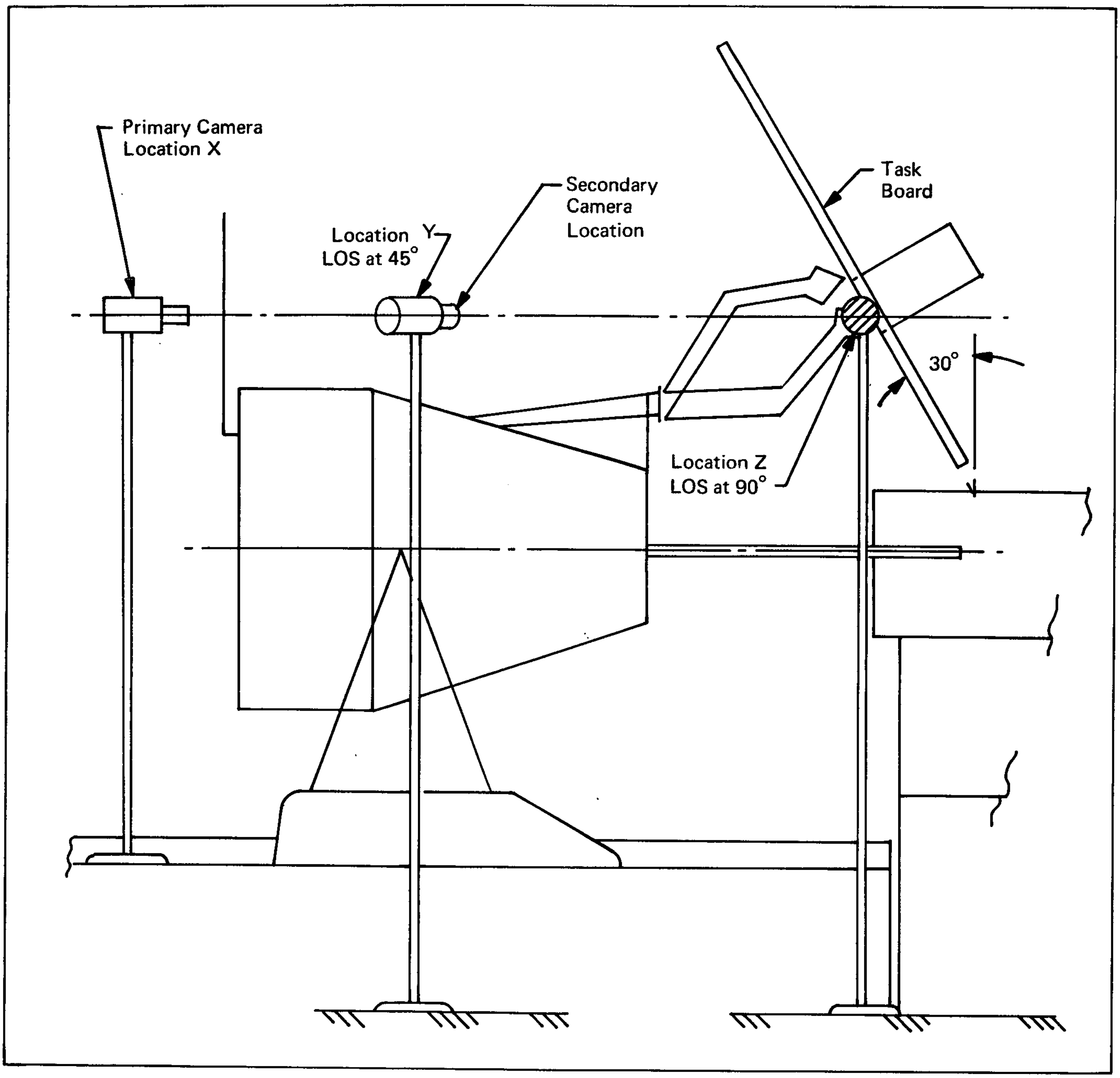

Figure A-9. Access Port Latch

4. Illumination of external surface and of interior of the compartment as described in 3.2.4.

5. Operator trial as indicated by matrix element (R)

6. Controller as indicated by matrix element (B).

7. Camera(s) as indicated by matrix element (A).

See Table A-3

8. Task board tilted forward 30° from vertical and ~ 38 cm (15 inches) away from foremost position on the track.

TABLE A-3
A3 x B3 x R3 SUMMARY OF EXPERIMENT RUNS FOR EXPERIMENT E3

			CONTROLLER TYPES		
		Replications	Controller Switch B_1	Master Controller B_2	Levers B_3
DISPLAYS	One Camera Normal to Task Board (Horizontal) A_1	R_1 R_2 R_3	$A_1B_1R_1$ $A_1B_1R_2$ $A_1B_1R_3$	$A_1B_2R_1$ $A_1B_2R_2$ $A_1B_2R_3$	$A_1B_3R_1$ $A_1B_3R_2$ $A_1B_3R_3$
DISPLAYS	Two Cameras, One Normal and One at 45° to Task in Horizontal Plane A_2	R_1 R_2 R_3	$A_2B_1R_1$ $A_2B_1R_2$ $A_2B_1R_3$	$A_2B_2R_1$ $A_2B_2R_2$ $A_2B_2R_3$	$A_2B_3R_1$ $A_2B_3R_2$ $A_2B_3R_3$
DISPLAYS	Two Cameras, One Normal and One Parallel to Task in Horizontal Plane A_3	R_1 R_2 R_3	$A_3B_1R_1$ $A_3B_1R_2$ $A_3B_1R_3$	$A_3B_2R_1$ $A_3B_2R_2$ $A_3B_2R_3$	$A_3B_3R_1$ $A_3B_3R_2$ $A_3B_3R_3$

9. Primary camera zoom setting: Access port to cover 90% of TV screen.

10. Left manipulator hand fully open; right hand holding the circular inspection mirror facing down.

11. Operator isolated to prevent direct viewing of the target.

12. Set teleoperator hands to 3 o'clock and 9 o'clock positions relative to the access port and approximately 25.4 cm (10 inches) away from the face of the board.

3.3.2 Initiate Task

Randomly select the combination of variables for the run to be visible from Table A-3.

Subtask 1 - REMOVE INSPECTION DOOR

1. (Start Timer) - Grasp handle on exterior of access door with the left hand.

2. Apply pressure across tabs 1 and 2 using left hand until lever is fully depressed against the stop

3. Remove access port with left hand - expose opening [TIME].

Subtask 2 - INSPECT:

4. Retain door in the left hand. Insert mirror held by the right hand into the inspection port.

*5 Orient mirror to identify objects and inspect for anomalies

*6 Position anomaly into the one inch diameter circle scribed on the mirror (Time)

Subtask 3 - REPLACE DOOR

7. Remove mirror from access port and outside the FOV of the primary camera

8. Align access door with hole

9. Position cover over access port (left hand)

10 Release lever (handle) until port is secure (Time)

3.3.3 Randomly select another element of the matrix and repeat experiment until all elements have been exhausted.

Control of extraneous variables, data recording and data analysis procedures are identical for all experiments and are presented in Section 7.0 of this appendix.

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*Because time was used as a criterion for performance, these steps of the procedure were modified to: Inspect the objects and then position terminal No. 4 of the electrical junction strip into a circle 2.5 cm (1.0 in) diameter scribed on the face of the inspection mirror.

4.0 EXPERIMENT E4 - ANTENNA INSTALLATION

4.1 OBJECTIVE

To evaluate the capability of the general purpose manipulator to install and fully extend a whip antenna, using standard antenna and electrical connector hardware.

Specific Elements to be Demonstrated

(a) Precise alignment of cylindrical (nesting) objects.

(b) Force application of sufficient magnitude and proper direction to permit engagement of a *standard* coaxial connector.

(c) Extension of telescoping antenna segments.

4.2 EXPERIMENTAL APPARATUS

4.2.1 Task Board

The experiment task is to install a whip antenna using a standard coaxial connector as base and then extend the telescoping sections of the antenna to their full travel. Figure A-10 shows details of the electrical connector and the antenna base.

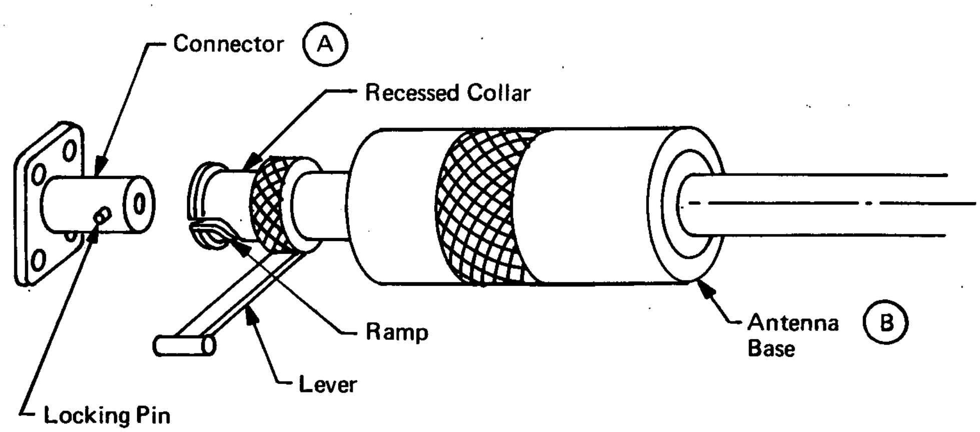


Figure A-10. Antenna Base and Electrical Connector for Experiment E4

The connector A, is rigidly affixed to the task board, with the centerline of the connector parallel to the plane of the task board. Part B, which constitutes the mating part for the connector and also the mounting base for the whip antenna is aligned and brought in contact with A. When the locking pin on the connector is aligned with the recessed collar, axial force is applied to initiate engagement of the connector. A force of 1.13 kg (2.5 lb) is required to engage the coupling. When the pin is engaged in the groove, the lever may be rotated to fully engage the connector, using the mechanical advantage of the lever and the mechanical advantage provided by the ramp to fully engage the pins and to lock the antenna in position.

The most difficult element of this task was expected to be the application of force to engage the pin into the collar. While only 1.13 kg (2.5 lb) of force is required to engage the connector when properly aligned well within the capability of the slave arm, (see paragraph 3.1.6 of Appendix B), when the force is applied at 30° to the axial centerline of the antenna, more than 5.5 kg (12 lb) are required to engage the connector. The latter is outside the capability of the manipulator. Without force feedback some difficulty was anticipated with this task because of inability to detect the presence and direction of residual forces. However, allowances were made to permit resolution of these problem areas with possible procedural changes during the qualification trials.

Rotation of the locking collar in the pitch plane is not possible with these manipulators. It was therefore necessary to attach a lever which converts the necessary rotary motion into a linear displacement motion, which the manipulator is known to be capable of performing.

After the antenna base is locked in place, the whip was extended to its limit of 61 cm (24 in.). The primary and secondary display systems described in paragraphs 7.1 and 7.2 of Appendix B were used.

4.2.2 Displays

The camera of the primary system was located along the mean centerline and slightly above the RMU, as in previous experiments. The second camera, however, was located directly above the task, viewing vertically down, see Figure A-11. Because the task requires precise motions in close coupled quarters, relocation of the secondary camera was necessary to prevent obscuring the task with the manipulator hands.

Camera combinations included:

Condition A1. A single camera at location X (Figure A-11).

Condition A2. Two cameras, one mounted as above, and the second at 90° to the line of sight of the first camera at location Y. Both cameras at locations X and Y and the task are contained in the same vertical plane.

Condition A3. A single camera at location Y. The camera at location Y and the task are contained in the same vertical plane.

Cameras were placed at constant distance from the task ~ 1.83 m (6 feet) and focused in the full-zoom condition.

4.2.3 Controllers

The controllers evaluated in this experiment include the Switch Controller, the Master Controller and Levers. – Section 6.0 of Appendix B gives complete description of the characteristics of these controllers.

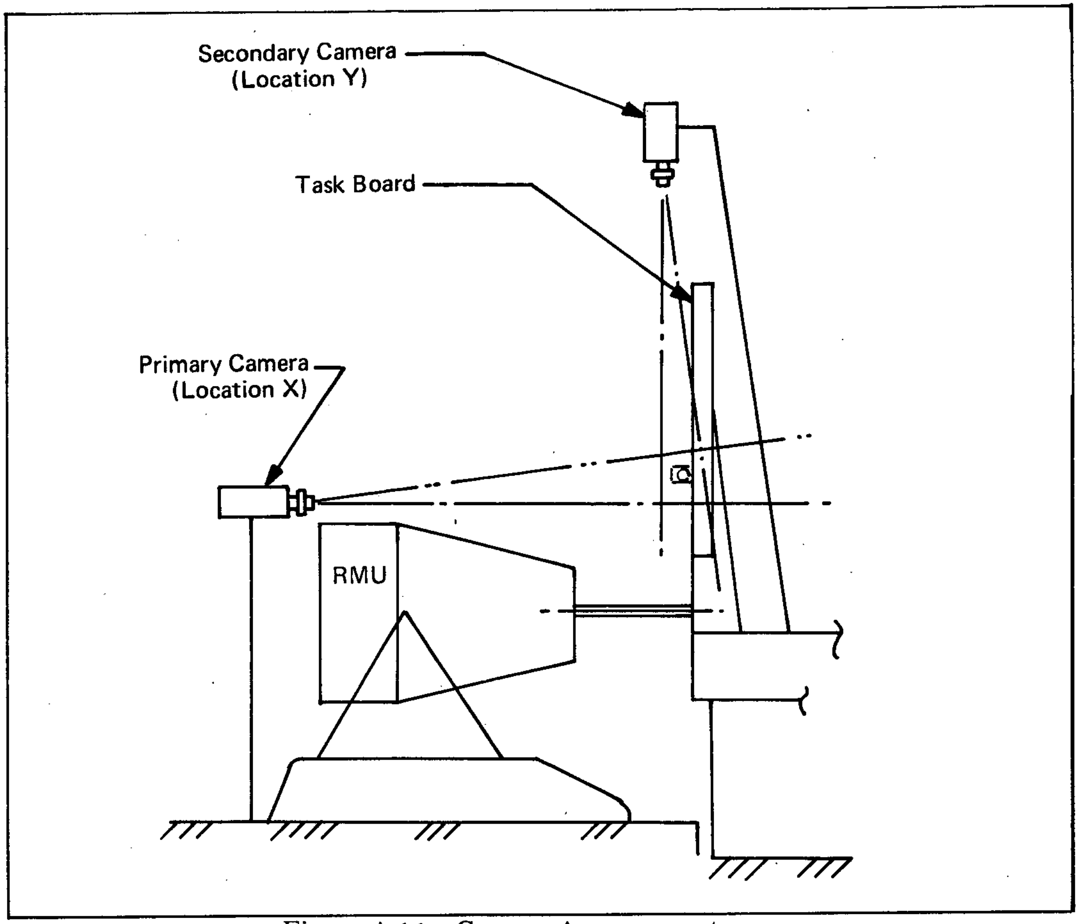


Figure A-11. Camera Arrangements

4.2.4 Illumination

The task was illuminated by a single 650W spotlight creating high contrast illumination. The spotlight was located adjacent to the camera at location X.

4.2.5 Operators

The same test subject (a Bell Test Pilot) trained to the level of consistency performed all experimental runs involving manipulation. Test subject qualifications appear in Section 7.0 of this appendix.

4.3 PROCEDURE

The operator was instructed of the task to be performed "Remove antenna. Reinstall the antenna to the connector base and extend whip."

4.3.1 Initial conditions:

1. RMU docked to task board, pad cushion "off"
2. RMU XMTR/RCVR "off"
3. RMU IR Target "off"
4. Task board illuminated by one 650 watt high-contrast spotlight normal to the task.

5. Operator trial as indicated by master element (R)
6. Controller as indicated by matrix element (B)
7. Camera(s) as indicated by matrix element (A)

See Table A-4

8. Task board vertical and 37 cm (15 inches aft of the foremost position on the track).
9. Primary camera at location X - zoomed for maximum magnification.
10. Secondary camera at location Y - zoomed for maximum magnification.

TABLE A-4
MATRIX OF EXPERIMENTAL RUNS A(3) X B(3) X R(3)

			CONTROLLER TYPES		
		Replications	Switch Controller B_1	Master Controller B_2	Levers B_3
DISPLAYS	One Camera Normal to the Task (Horizontal) A_1	R_1 R_2 R_3	$A_1B_1R_1$ $A_1B_1R_2$ $A_1B_1R_3$	$A_1B_2R_1$ $A_1B_2R_2$ $A_1B_2R_3$	$A_1B_3R_1$ $A_1B_3R_2$ $A_1B_3R_3$
DISPLAYS	One Camera Parallel To the Task Board in Vertical Plane A_2	R_1 R_2 R_3	$A_2B_1R_1$ $A_2B_1R_2$ $A_2B_1R_3$	$A_2B_2R_1$ $A_2B_2R_2$ $A_2B_2R_3$	$A_2B_3R_1$ $A_2B_3R_2$ $A_2B_3R_3$
DISPLAYS	Two Cameras, One Normal and One Parallel to Task Board in Vertical Plane A_3	R_1 R_2 R_3	$A_3B_1R_1$ $A_3B_1R_2$ $A_3B_1R_3$	$A_3B_2R_1$ $A_3B_2R_2$ $A_3B_2R_3$	$A_3B_3R_1$ $A_3B_3R_2$ $A_3B_3R_3$

4.3.2 Initiate Task

Randomly select the combination of variables for the run to be made from Table A-4. Note this task requires only a single hand operation. The right hand of the manipulator will be used.

Subtask 1 - UNLOCK AND DISENGAGE

1. [START TIMER] - Align tip of manipulator hand (open position) with T-bar on lever and rotate it 90° by applying a downward force (displacement).

2. Align "V" notch in right hand with knurled section of antenna base; close hand.

3. Remove antenna from base connector by applying force (command) in the yaw plane. [RECORD TIME]

Subtask 2 - INSTALL LOCK AND EXTEND

4. [START TIMER] - Reduce separation distance between connector and antenna base to approximately 6 mm (1/4 inch).

5. Align groove on the base of the antenna with locking pin on connector.

6. Advance antenna until it is in contact with the connector - check pin alignment.

7. Apply pressure (command displacement along centerline of antenna) until the locking pin of the connector is engaged in the collar.

8. Release antenna base.

9. Using the same hand, push lever up until the pin is locked in the collar.

10. Extend whip sections by pulling (horizontally) on each successive section until fully extended. Start with the smallest diameter unit.

11. Rest right hand at the 3 o'clock position. [RECORD TIME]

4.3.3 Randomly select another element of the matrix and repeat experiment until all elements have been exhausted.

Control of Extraneous Variables, data recording, and data analyses procedures are identical for all experiments and are presented in Section 7.0 of this appendix.

5.0 EXPERIMENT E5 - FLUID COUPLING

5.1 OBJECTIVE

To establish the utility of a general purpose manipulator to engage and disengage a coupling suitable for fluid transfer.

Specific elements to be demonstrated

(a) Precise alignment of coupling elements
(b) Manipulation of levers (special tools) to provide force amplification.

5.2 EXPERIMENTAL APPARATUS

This experiment demonstrates the feasibility operations required to engage and disengage a fluid coupling on the external surface of a spacecraft suitable for propellant replenishment, cryogenic replenishment for IR sensors or high pressure gases (O_2) for life support systems.

5.2.1 Task Board

The coupling selected for this experiment is designed and fabricated for space use. It is a quick disconnect, which engages and disengages with a minimum (zero) spillage of the fluid handled. It incorporates check valves on both sides of the separation line which seal upon disengagement. The coupling is shown in Figure A-12 disengages under power provided by an internal spring when the release tab is depressed. Engagement, however, requires application of 8.2 kg (18 lbs) of force over approximately 1.3 cm (1/2 in.) travel. Since the manipulator force capability at the tip is limited to 2.27 kg (5 lbs), engagement is not possible unless some means of force amplification can be devised. The latter is accomplished through a lever arrangement shown in Figure A-12.

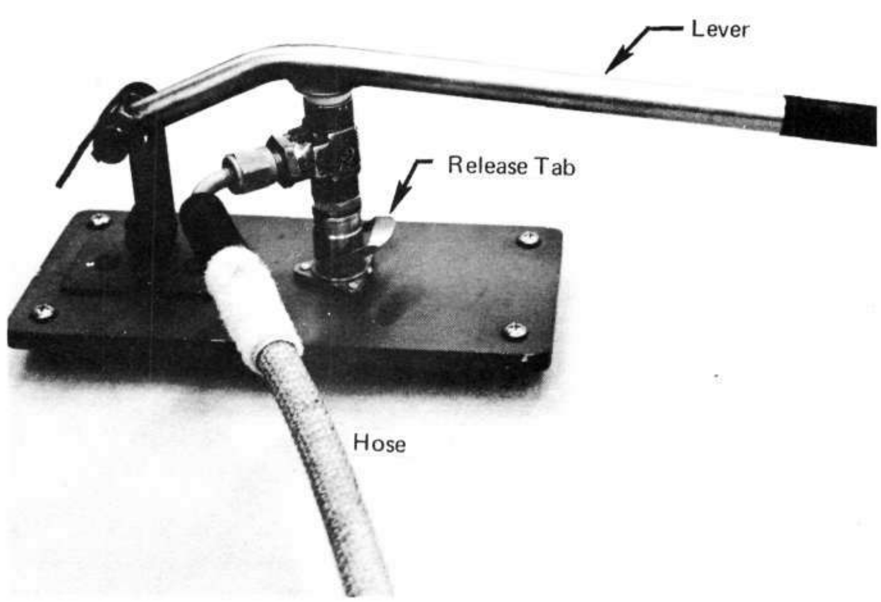


Figure A-12. Fluid Coupling and Lever Arrangement

The lever is manipulated with the right hand, while the left hand aligns the mating parts of the coupling. The male portion of the coupling is affixed to the flexible hose transfer line through a standard aluminum alloy "Tee" fitting. The two outlets of the tee, at right angles to each other, (Figure A-12), are used to duct the fluid to the coupling. The third outlet is sealed with a teflon plug which reduces sliding friction between the tee and the lever during engagement of the coupling. To accommodate some residual misalignment, the male portion of the fitting is held by the flexible hose about 5 cm (2 inches) away from the fitting itself. This permits some deflection to take place during engagement without imposing undue strain to the left arm or to the work piece. When the male portion of the disconnect is depressed to the proper depth, the coupling locks automatically.

5.2.2. Displays

The three conditions involving the numer of cameras and camera locations which constitute independent variables are listed below and shown in Figure A-13.

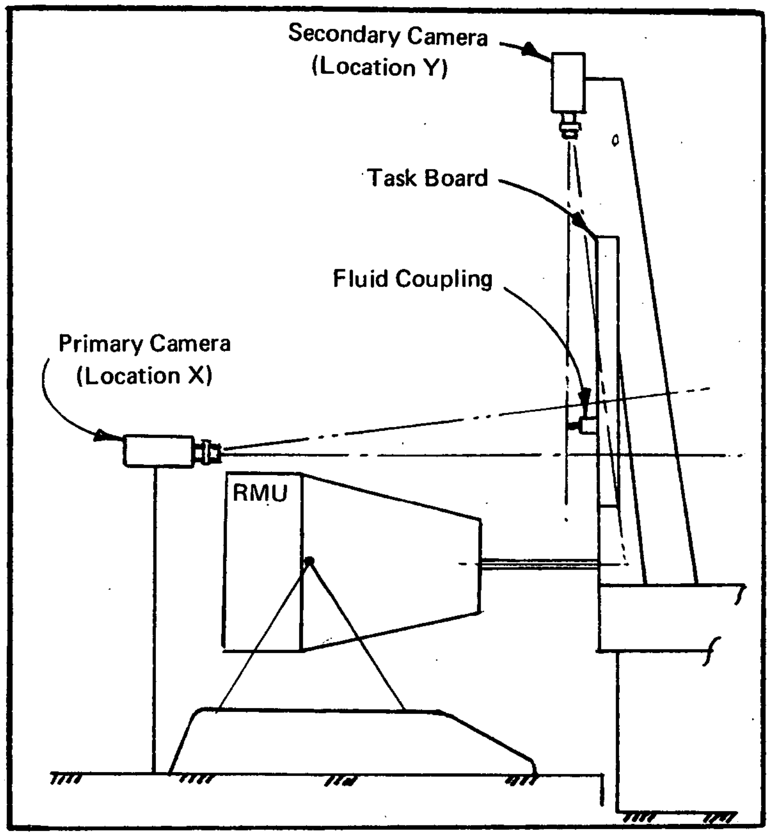


Figure A-13. Camera Placement

Condition A1 - A single camera at location X slightly above and behind the manipulator arms.

Condition A2 - Two cameras, one as in A1 and the second camera at location Y with its LOS vertical and intersecting the LOS the first camera at the task.

Condition A3 - A single camera at location Y.

Regardless of their angular orientation, all cameras are equidistant from the task at ~ 1.83 m (6 ft). Characteristics of the equipment used in these arrangements, identified as primary or secondary display systems are described in Sections 7.1 and 7.2 of Appendix B.

TABLE A-5
A(3) X B(3) X R(3) SUMMARY TABLE

			CONTROLLER TYPES		
		Replications	Switch Box B_1	Master Controller B_2	Levers B_3
DISPLAYS	One Camera Normal to the Task (Horizontal) A_1	R_1 R_2 R_3	$A_1B_1R_1$ $A_1B_1R_2$ $A_1B_1R_3$	$A_1B_2R_1$ $A_1B_2R_2$ $A_1B_2R_3$	$A_1B_3R_1$ $A_1B_3R_2$ $A_1B_3R_3$
	One Camera Normal to the Task Board With Mirror A_2	R_1 R_2 R_3	$A_2B_1R_1$ $A_2B_1R_2$ $A_2B_1R_3$	$A_2B_2R_1$ $A_2B_2R_2$ $A_2B_2R_3$	$A_2B_3R_1$ $A_2B_3R_2$ $A_2B_3R_3$
	Two Cameras, One Normal and One Parallel to the Task Board in Vertical Plane A_3	R_1 R_2 R_3	$A_3B_1R_1$ $A_3B_1R_2$ $A_3B_1R_3$	$A_3B_2R_1$ $A_3B_2R_2$ $A_3B_2R_3$	$A_3B_3R_1$ $A_3B_3R_2$ $A_3B_3R_3$

5.2.3 Controllers

The controllers investigated in this experiment include the Switch Box, Master Controller and Levers. Section 6.0 of Appendix B gives complete descriptions of the characteristics of these controllers.

5.2.4 Illumination

High contrast illumination produced by a single 650 W spot light located at 45° to the camera at location X and at approximately the same height as the camera.

5.2.5 Operators

The same test subject (a Bell Test Pilot) trained to a level of consistency performed all experimental runs involving manipulation. Test subject qualifications appear in Section 7.0 of this Appendix.

5.3 PROCEDURE

The operator was instructed of the task to be performed "Engage Fluid Coupling using the lever provided for force amplification - Disengage coupling and stow flexible hose."

5.3.1 Initial Conditions

1. RMU docked to task board, pad cushion "off"
2. RMU XMTR/RCVR "off"
3. RMU IR Target "off"
4. Task board illuminated by a single 650 watt high contrast spot light located at 45° to the camera at location X.
5. Operator Trial as indicated by matrix element (R)
6. Controller as indicated by matrix element (B) — TABLE A-5
7. Camera placement as indicated by matrix element (A)
8. Task board vertical and ~ 38 cm (15 inches) from foremost position on track.
9. Primary camera location X zoomed in so as to display an area of ~ 900 cm^2 (1 ft^2) of the task board in the display.
10. Auxiliary camera located at Y zoomed in so that its beamwidth is ~ 30.5 cm (12 inches) across the point where it intercepts the task.
11. Coupling disengaged - male portion of coupling held with left hand of manipulator; lever is held with the right hand.
12. Operator stationed at the manipulator controller facing away from the task board and commanding operations through cues revealed to him by the visual displays only (one or two monitors).
13. Operator trained to the level of consistency.

5.3.2 Initiate Task

Randomly select the combination of variables for the run to be made from Table A-5.

Subtask 1 - ENGAGE

1. [START TIMER] Align and engage coupling with its mating part on the spacecraft using the left hand.
2. Engage lever (held in right hand) with the fitting provided on the task board.

3. Depress coupling until it engages (cue: coupling release tab pops up). [RECORD TIME]

4. Retain left hand on the flexible coupling hose. (This represents the period of fluid transfer).

Subtask 2 - DISENGAGE

5. [START TIMER] - Remove lever from the fitting on the task board and orient it approximately normal to the task board surface.

6. Depress coupling release tab with T-bar until disengagement is complete (spring loaded coupling automatically separates).

7. Position right and left arms at 9 o'clock and the 3 o'clock position within the field of view of the camera. [RECORD TIME]

5.3.3 Randomly select another element of the matrix and repeat experiment until all elements have been exhausted.

Control of Extraneous Variables, Data Recording and Data Analysis Procedures are identical for all experiments and are presented in Section 7.0 of this Appendix.

6.0 EXPERIMENT E6 - MANEUVERING AND DOCKING

6.1 OBJECTIVES

To evaluate the effect of displays, control dynamics and docking aids on maneuvering and docking accuracy and energy expenditure.

Specific elements within these objectives include:

a) Maneuvering to a specified position with respect to a target using a predetermined path.

b) Stationkeep with sufficient accuracy with respect to a point or area on the target to permit a gross inspection and identification of external structural flaws.

c) Evaluate maneuvering accuracy in the acceleration command modes and in the rate command mode.

d) Evaluate maneuvering and docking accuracy using TV with stadia lines on the TV raster versus TV with meter type readout displays for range and range rate information.

6.2 EXPERIMENTAL APPARATUS

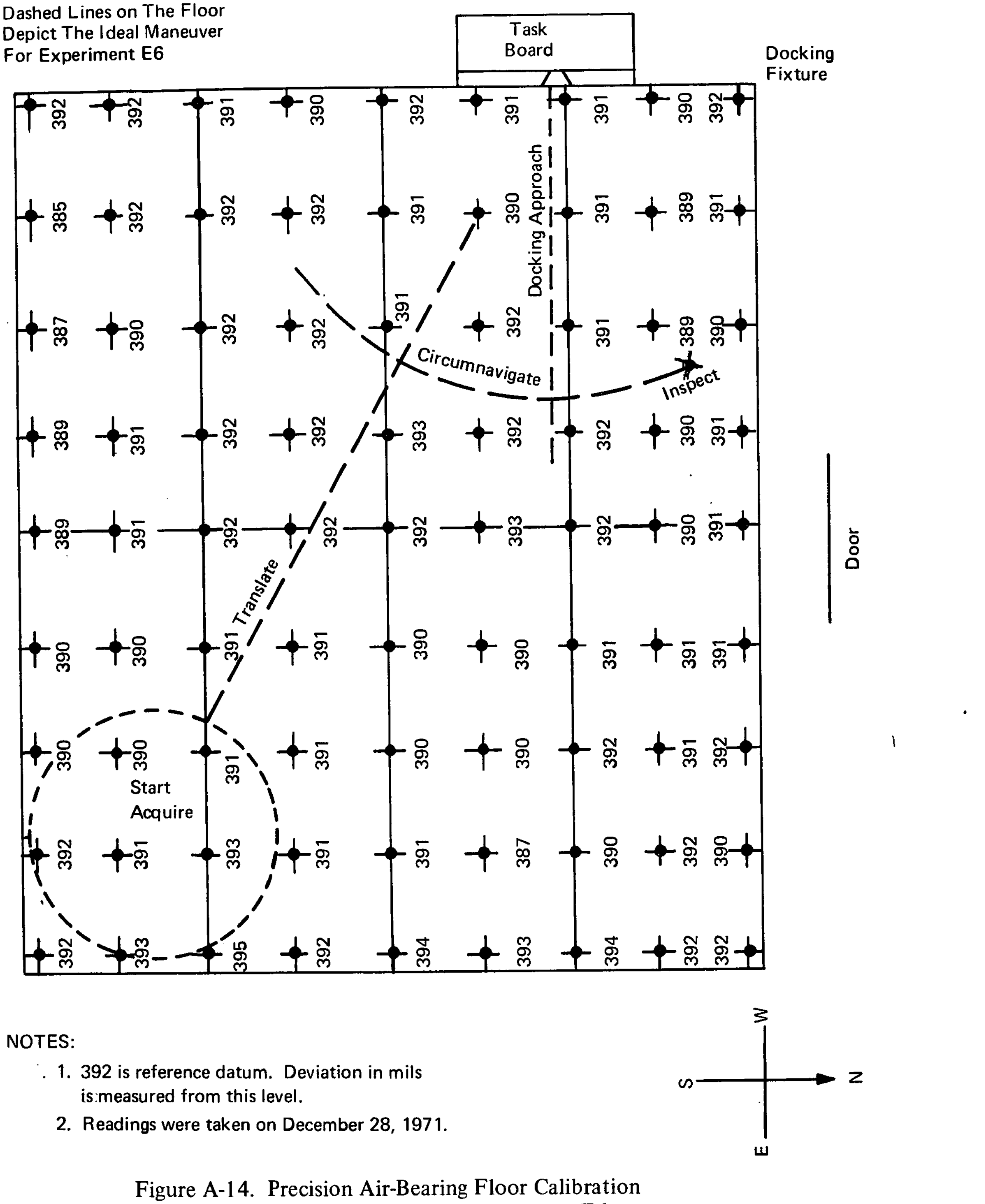
Evaluation of inspection and docking maneuvers dictates the use of a smooth, flat and level floor, to minimize extraneous forces and frictional loses which cannot be distinguished from, and may be interpreted as drift rates. Therefore, in preparation for this experiment, the precision 6.10 x 7.3 m (20 x 24 ft) floor was calibrated for levelness and flatness to the limits shown in Figure A-14. To make possible the evaluation of accuracy measures during the various phases of maneuvering, the ideal maneuver was outlined on the surface of the precision floor. This outline was not seen by the operator during the experimental runs.

The inspection was carried-on in the stand-off mode. The inspection vehicle approaches the target satellite and stationkeeps sufficiently close (~ 2.75 m (~ 9 ft)) to identify the location and nature of the flaws on the solar panel.

6.2.1 Task Board

The task board for this experiment consisted of a mockup solar array containing several damaged solar cells. Cell damage is such that it could have been caused by meteoroid showers (small diameter penetrations, fractured cells or cells with eroded surface). Figure A-15 shows the simulated solar array.

The task board permits relocation of the damaged cell(s) within the boundary of the panel. Row and column markings have been added for identification of the damaged cell by the operator. The damaged cell(s) may be relocated at initiation of each run.



NOTES:

1. 392 is reference datum. Deviation in mils is measured from this level.
2. Readings were taken on December 28, 1971.

Figure A-14. Precision Air-Bearing Floor Calibration for Maneuvering and Docking, Experiment E6

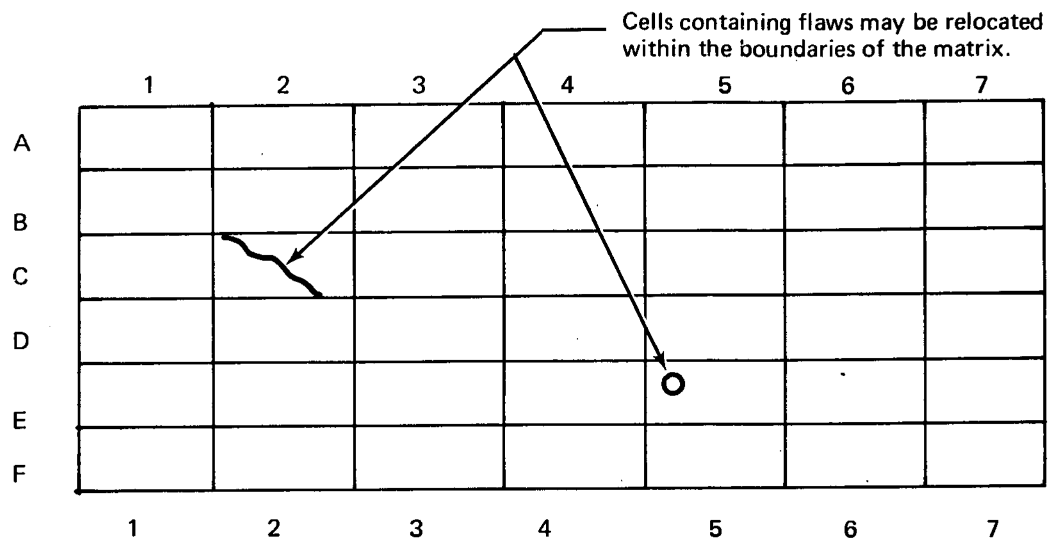


Figure A-15. Simulated Solar Array

6.2.2 Displays

The combination of displays which constitute independent variables for maneuvering and docking experiments include the following:

Condition A1. Video Display - Use of a single video raster to display the image of a camera boresighted parallel to the RMU mean centerline. Focus and 4:1 zoom controls are available to the operator at a remotely located flight control console as are meter type range and range rate displays.

Condition A2. Video display as in (1) with stadia rings to permit ranging. All other displays were obscured from the operator's view.

6.2.3 Control Dynamics

The following control dynamics were investigated. Control System characteristics are described in Section 3.1.3 of Appendix B.

Condition B1. Controlling the vehicle's attitude using acceleration commands.

Condition B2. Controlling the vehicle's attitude using rate command. A special feature which holds the vehicle's attitude in the last commanded position is also inherent in this mode of control

6.2.4 Docking Aids

Docking aids constitute the third set of independent variables investigated in this experiment. Two such conditions were investigated.

Condition C1. Gun Sight - Use of the tip of the docking boom which extends forward of the vehicle and is aligned with the camera LOS to provide body alignment cues - Figure A-16.

Condition C2. Reticle - A transparent film placed on the TV monitor incorporating cross hairs to yield cues for alignment in docking.

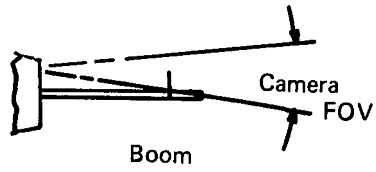


Figure A-16. Gunsight

6.2.5 Illumination

All experimental runs were made using general illumination produced by overhead fluorescent lights.

6.2.6 Operators

The same test subject (a Bell Test Pilot), trained to the level of consistency, performed all experimental runs involving maneuvering and docking. Test subject qualifications appear in Section 7.0 of this appendix.

6.3 PROCEDURE

Instruct the operator to acquire and approach the target, inspect the solor panel from a distance of 9 feet, identify the column and row of the damaged solar cell, and finally dock with the target.

The matrix portrayed in Table A-6 represents the experimental design of the RMU maneuvering and docking study, and is so composed as to meet the requirements for a three-way analysis of variance.

TABLE A-6

A(2) x B(2) x C2 x R3 SUMMARY TABLE

DOCKING AID ⇒			C_1 GUN SIGHT		C_2 RETICLE	
		Control Mode ⇒ / Operator Trial ⇓	Control Dyn. B_1 Accel. Command	Control Dyn B_2 Rate Command	Control Dyn. B_1 Accel. Command	Control Dyn. B_2 Rate Command
DISPLAYS	A_1 TV With R & $\dot{R}$ Display	R_1	$A_1B_1C_1R_1$	$A_1B_2C_1R_1$	$A_1B_1C_2R_1$	$A_1B_2C_2R_1$
		R_2	$A_1B_1C_1R_2$	$A_1B_2C_1R_2$	$A_1B_1C_2R_2$	$A_1B_2C_2R_2$
		R_3	$A_1B_1C_1R_3$	$A_1B_2C_1R_3$	$A_1B_1C_2R_3$	$A_1B_2C_2R_3$
	A_2 TV with Stadia Rings	R_1	$A_2B_1C_1R_1$	$A_2B_2C_1R_1$	$A_2B_1C_2R_1$	$A_2B_2C_2R_1$
		R_2	$A_2B_1C_1R_2$	$A_2B_2C_1R_2$	$A_2B_1C_2R_2$	$A_2B_2C_2R_2$
		R_3	$A_2B_1C_1R_3$	$A_2B_2C_1R_3$	$A_2B_1C_2R_3$	$A_2B_2C_2R_3$

6.3.1 Initial Conditions

1.	Record propellant quantity on RMU	Ascertain sufficient quantity exists to complete run
2.	Record battery status on RMU	
3.	Run-up CMG's as dictated by Matrix Element 'B' Control Dynamics	Table A-6
4.	Activate the following RMU systems: TV camera, Data Link, Propulsion	
5.	Install reticle on TV monitor (console) and obscure R&R displays as dictated by matrix element 'A'	Table A-6
6.	Orient RMU away from the target ~ 180°	
7.	Obscure operator's direct view of the RMU and of the target	
8.	Position defective solar cell(s) in the solar cell array	
9.	RESET docking Control on Flight Console	
10.	Turn IR target "ON"	
11.	Float the RMU on its platform	
12.	Activate RMU thrusters (from the console)	

6.3.2 Initiate Task

1. Select "MANUAL" Mode of Control
2. Activate Thrusters [START TIMER]
3. Initiate Acquisition Maneuver
   a) Null out pitch attitude
   b) Command Yaw-Right (~ 5 deg/sec) and continue until target is sighted in the TV monitor
   c) Stop angular motion and boresight on target
4. Approach target along LOS at ~ 9 cm/sec (0.35 fps). Stop at 2.75 m (9 ft).

C.3

5. Circle target at 2.75 m (9 ft) to acquire a view which is normal to the solar panel.

6. Stop RMU; adjust zoom and focus controls to permit detailed inspection of solar cells. Identify row and column of defective cell(s).

7. Command RMU to a position normal to the docking fixture 2.75 m (at 9ft). Stop (mark Recorder traces to separate maneuvering from docking).

8. Approach docking fixture at ~ 9 cm/sec (0.35 fps). Enter probe at 3 to 0.6 cm/sec (0.1 to 0.2 fps). [TIME]

6.3.4 Randomly select another matrix element - satisfy initial conditions and repeat experiment. When all elements have been exhausted, the experiment is completed.

Control of Extraneous Variables, Data Recording and Data Analysis Procedures for this Maneuvering and Docking Experiment are presented in Section 7.0 of this Appendix.

7.0 ELEMENTS COMMON TO ALL EXPERIMENTS

Control of Extraneous Variables, Data Recording, and Analysis Procedures common to all experiments are documented in this section of Appendix A.

7.1 CONTROL OF EXTRANEOUS VARIABLES

7.1.1 Training Criteria

In order to ensure that the operator had been adequately trained, prior to the collection of experimental data, a special procedure was developed to determine whether performance with the system to be evaluated had reached asymptote.

To measure a learning process, it is necessary to choose some quantity that changes as the individual learns and becomes statistically constant when he ceases to learn. For certain activities one of the easiest and most useful quantities is the time it takes an individual to perform a particular task. To determine when the individual has ceased to learn, it is necessary to devise a statistical test that determines when the time to do a particular task is essentially constant.

The method devised accumulates samples from each learning trial (time to perform a particular task) until the mean of the quantity becomes constant with fixed variance.

Five trials were selected as the minimum number required to obtain a reliable mean and variance. Ten trials were therefore collected and the mean and variance of trials 1 through 5 compared with those of 6 through 10, using a 't' test and an F test respectively.

A significant difference in the t or F test with $\alpha \geqslant 0.05$ was grounds for inferring a continuing learning process, and a further trial was run and the first trial ignored; t and F tests were then performed to compare trials 2 through 6 with trials 7 through 11. This process achieved until no significant difference of either F or t test could be obtained.

A computer program was written to perform the above method and was used successfully via a RAX terminal. Complete details of the assumptions and equations used in the training program are presented in Appendix D.

7.1.2 Test Subject Qualifications

A single subject was used throughout the series of experiments reported herein. This subject was a healthy male aged: 35, weight: 170 lb, height: 5 ft 8 inches.

His occupation is Manager, Flight Test Operations and Chief Test Pilot. He holds the degree of B.S. in Electrical Engineering and is a graduate of the Empire Test Pilot School, Farnborough, England. In addition to his work in this study, his experience includes the operation of rocket-powered small-lift devices in a variety of flight control configurations including kinesthetic control. He has also operated a 1/6 g moving base simulation of lunar handling characteristics.

His total flying hours are:

Jet	127	Turboprop	5	V/STOL	77
Reciprocating	868	Helicopter	2,207		

Fatigue effects were minimized by limiting the subject to a total of 4 hours work per day, with 5 minutes rests between trials.

7.2 INSTRUMENTATION AND DATA RECORDING

The instrumentation for the data collection effort was designed to provide a permanent record of the raw data gathered during the test program and to permit data reduction and analysis on a non-real time basis.

7.2.1 Data Recorded on Manipulation Tests

Two synchronized eight-channel Offner recorders were used to provide a continuous record of the potentiometer voltages for each of the 14 manipulative joints. Angular displacement of each joint was recorded for the entire duration of the test. The 7 channels of each recorder were assigned to record the following function:

Channel 1	Shoulder Yaw	Channel 5	Wrist Pitch
Channel 2	Shoulder Pitch	Channel 6	Wrist Roll
Channel 3	Shoulder Roll	Channel 7	Hand
Channel 4	Elbow (Pitch)		

The eighth channel of each recorder was used to record the errors committed during execution of the task at the appropriate instant of occurrence.

Input voltages representing maximum joint deflection were ±5V. The maximum displacement was seldom used however. Depending on the task being performed, the test director changed the scale factors on the recorder to achieve the largest possible amplification. Appropriate scale factors for each run are documented on the recorder traces. The recorders were situated in close proximity to the test director to provide a real-time display of the operational status of all signals. Figure A-17 shows a typical trace of the recorded data.

Task and subtask durations were also derived from the recorder traces from markings placed on the record by the test conductor. The following workload and joint usage measures were derived from the recorded data.

Workload Measures

Mean time an arm is moving Mean time between movements Integrated absolute time arm is moving Integrated absolute time between moves Time moved/time not moved	Use strip chart recorder. 14 channel 5 mm/sec. Record Manipulator Pot. voltages vs time

Joint Usage

Use per trial (count the number of times each joint is used per trial). Total duration of joint usage (count total duration each joint is used during trial). Joint use/Total use-Ratio of total duration one joint is used to total duration all joints are used.	Use strip chart recorder 14 channel 5 mm/sec - Record Manipulator Pot. Voltages vs. time

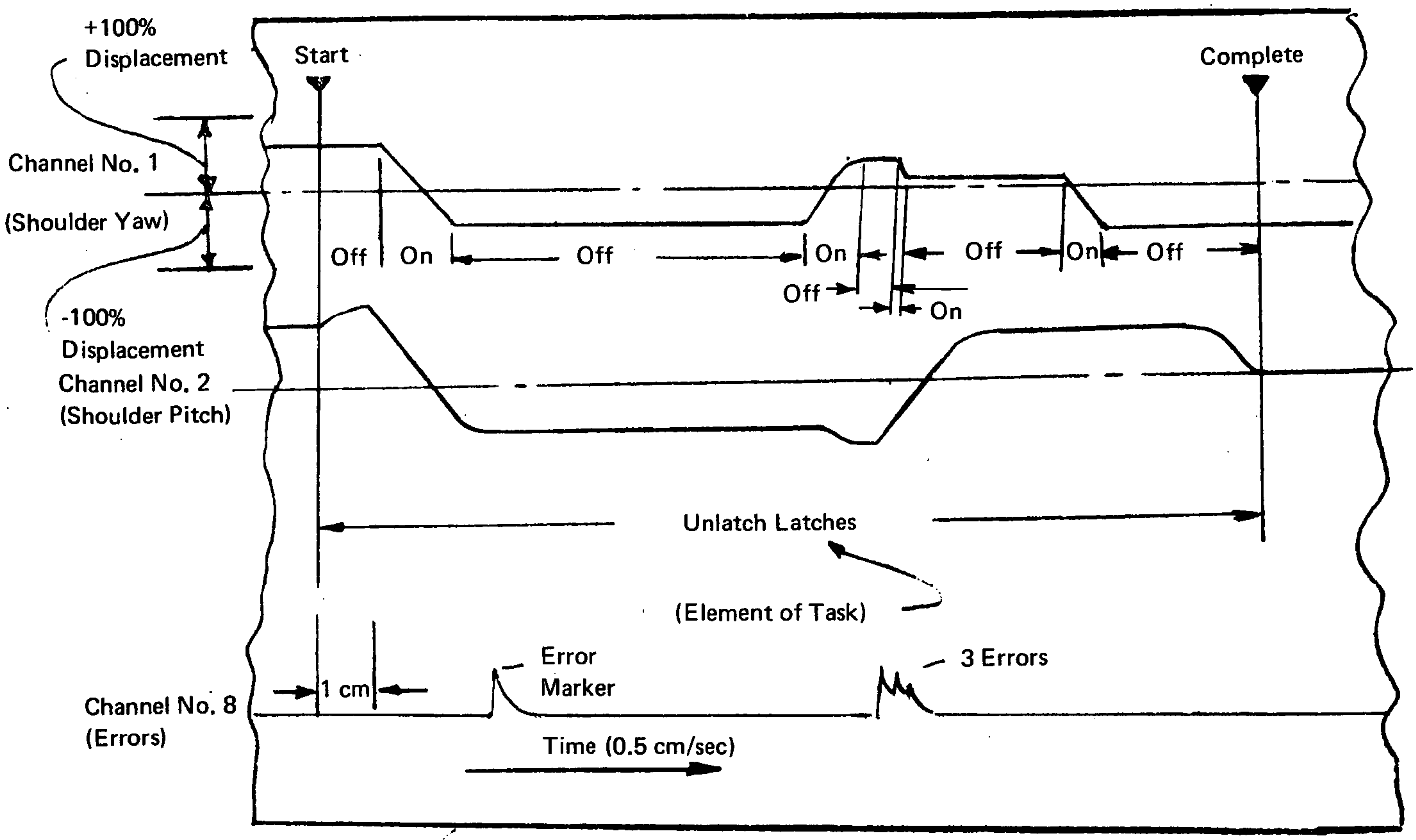


Figure A-17. Typical Recorder Trace for Manipulation Task

7.2.2 Data Recorded for Maneuvering and Docking Tests

The techniques involved in the collection and recording of data for evaluation of maneuvering and docking tests varied considerably from those used for manipulation.

Flight vehicle body rates and displacements were the dependent variables for these experiments. To record these funtions, appropriate sensors were installed on the RMU vehicle and their outputs telemetered to the control console as analog voltages using the RMU data link. Because some of these same signals are used in the RMU control loop, (in R, $\dot{R}$). It was necessary to fabricate and install buffer electronics for each channel recorded for subsequent evaluation.

One eight-channel Offner recorder was used to record the following functions:

Channel 1	Range
Channel 2	Range Rate
Channel 3	Fuel
Channel 4	Battery Status
Channel 5	Pitch displacement
Channel 6	Roll displacement
Channel 7	Not used

Channel 8 Used by test director to mark phases of the maneuver

a) Acquisition
b) Translation
c) Circumnavigation
d) Inspection
e) Docking approach

The two additional parameters needed for maneuvering and docking evaluation, Y-translation and vehicle yaw require extensive instrumentation to achieve. To overcome this difficulty, each run was video taped with a camera located above the precision floor. The ideal maneuver was outlined on the floor using 12-inch long dashed lines. (These lines were not seen by the operator.) By playing back the tape, the action could be stopped and the deviation in y-displacement and vehicle yaw measured. Parallax problems were alleviated by using the dashed lines painted on the floor (see Figure A-14) as unit measures, and markings on the air bearing platform very close to the floor for angular measurements.

The following performance parameters were derived from the data recorded with the Offner and Video Tape.

- Fuel expenditure
- Battery expenditure
- Average range rate during translation
- Maximum range rate achieved
- Error in pitch, yaw and roll attitude
- Deviation from the ideal path during translation and circumnavigation maneuvers
- Total time to accomplish the task and its subtasks
- Values of R, $\dot{R}$ at the instant the docking probe made contact

One additional parameter, lateral miss-distance during the docking maneuver was manually recorded. The test director also manually recorded work load performance parameters and significant comments of the operator concerning difficulty of control.

The following subjective information will be collected both for its intrinsic interest and for correlation with the objective data.

- Experimenter's Observations - Any occurrences of interest, e.g., novel maneuvering technique, peculiar difficulties, etc. were recorded by the experimenter.

- Operator's Comments - The operator was encouraged to make comments while performing, regarding the response of the system.

- Operator's Ratings - The operator was asked to rate each run in terms of a workload scale and a performance scale.

Workload Imposed:	3	2	1	0	-1	-2	-3
	Very Light	Light	Mod. Light	Average	Mod. Heavy	Heavy	Very Heavy

(How hard did you have to work?)

Performance:	3	2	1	0	-1	-2	-3
	Very Good			Average			Very Poor

(How well you did as compared with how well you could have done?)

7.3 DATA ANALYSIS PROCEDURES

7.3.1 Analysis of Variance

All the parametric data for each of the A x B x C combinations representing displays, control dynamics and docking aids were plotted in 2 dimensions to see whether there appear to be "prima facie" effects and trends. When this was established a three-way analysis of variance was performed on each dependent parametric variable.

The particular model chosen, Equation 1, is a modification of McNemar's[1] Case XII, extended from a 3-way to a 4-way classification. This model does not permit the testing differences between subjects since only 1 observation per ABC condition is made.

$$yx = \frac{yb^2}{yt^2} \qquad (1)$$

where yb^2 = sum of squares between groups

and yt^2 = total sum of squares

The significance of the correlation ratio is tested using an F test.

$$F = \frac{yb^2/(k-1)}{yw^2/(n-k)} \qquad (2)$$

k = number of groups
n = number of observations
yw^2 = sum of squares within groups

7.3.2 Multiple Correlation

In order to determine the degree of association among all dependent variables used, a multiple correlation computer program was written for use via RAX to generate multiple correlation matrices

(1) Psychological Statistics, Q. McNemar, J. Wiley, Third Edition

for the Pearson Product Moment Correlation Coefficient (Γ). The computational formula is expressed below; x and y represent any two variables being correlated, n is the number of observations per variable.

$$\Gamma = \frac{\dfrac{\Sigma\, x\, y}{n - 1}}{\sqrt{\left(\dfrac{\Sigma\, x^2}{n - 1}\right)\left(\dfrac{\Sigma\, y^2}{n - 1}\right)}} \qquad (3)$$

APPENDIX B

EXPERIMENT EQUIPMENT AND ITS USE

This Appendix contains detailed descriptions of the physical and functional characteristics of equipment used in the experiment program and sets forth general guidelines for the use of these equipment.

The equipment description contained herein include those of the Bell 5 degree-of-freedom simulation facility, and the equipment furnished by NASA as GFE for the purpose of integration with the Bell facility and conduct of the manipulation experiments.

PART I - CHARACTERISTICS OF HARDWARE USE IN THE EXPERIMENT

The teleoperator system shown in Figure B-1 consists of the following pieces of equipment.

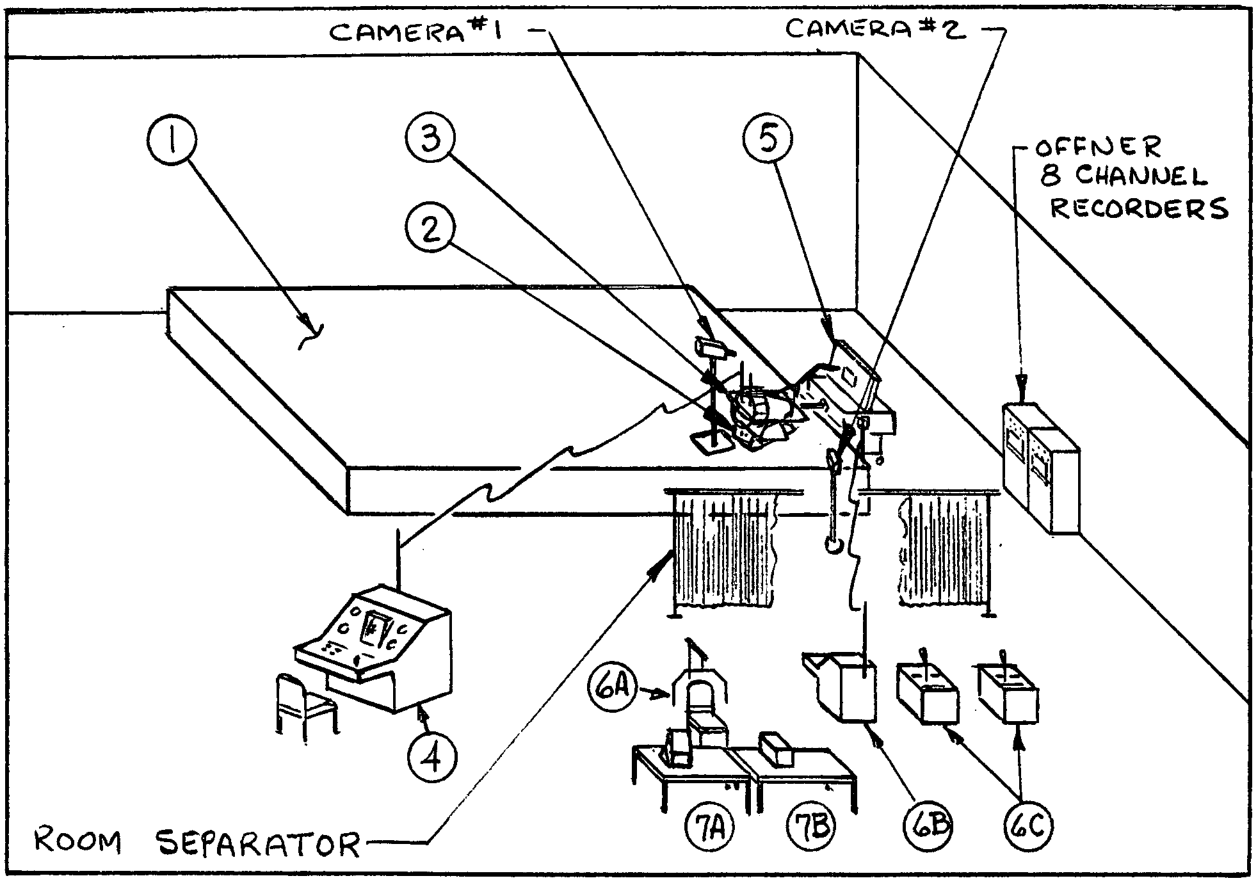


FIGURE B-1 - TELEOPERATOR SYSTEM

1. Precision Air Bearing Floor 2. Air Bearing Platform 3. Remote Maneuvering Unit 4. Flight Control Console	Bell RMU Facility
5. Task Board Fixture and Inserts 6. Manipulator Control Console	Bell Built Equipment for this Program
a. Master-Slave Controller* b. Switch Box Controller c. Lever (Joy Stick) Controller* 7. Displays a. High Resolution TV b. Standard TV	Equipment Furnished to Bell Aerospace as GFE

A brief description of the characteristics for the above equipment follows.

*Designed and Fabricated by Rancho Los Amigos Hospital Inc.

1.0 THE PRECISION FLOOR

The Precision Floor shown in Figure B-2, is a flat, level and smooth surface which in conjunction with the Air Bearing Platform provides an essentially friction-free environment where precise space rendezvous and docking maneuvers can be simulated with a high degree of fidelity.

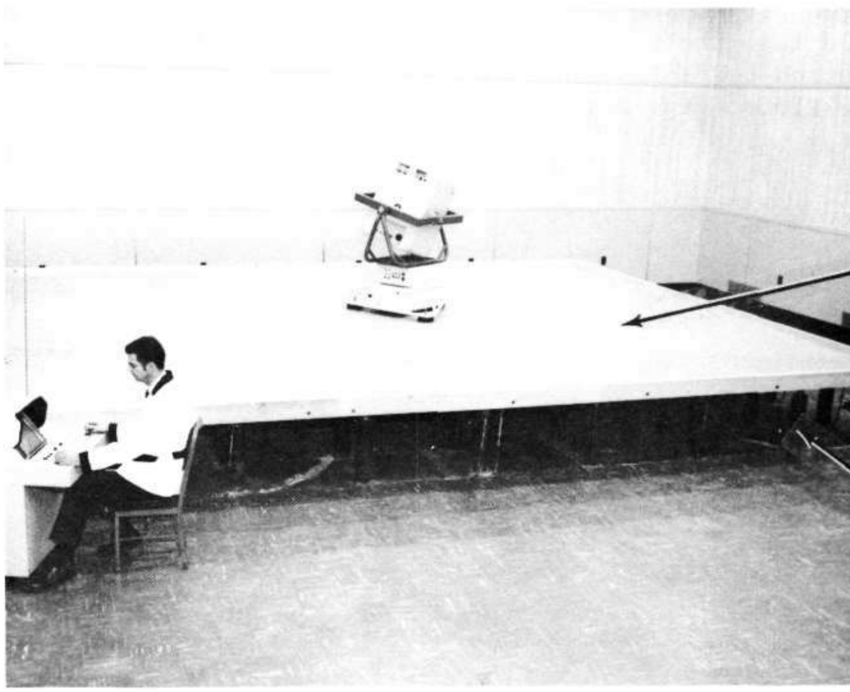


FIGURE B-2 - PRECISION AIR BEARING FLOOR

The 480 square foot floor has the following characteristics

- Level - .002 inches overall
- Flatness - ±.001 inches within any 3 ft. radius
- Smoothness - 4×10^{-6} RMS over entire surface

The floor is constructed of 12 aluminum plates, 2 inches thick bolted together to form one continuous surface. This surface is floated on 81 equally spaced jacks and pre-loaded with tension ties to permit initial leveling and subsequent calibration. Following leveling and flatness adjustments, the floor was coated with several layers of polyurethane and lapped to a fine smooth finish. Dimensional stability is ensured by controlling the simulation room temperature within 5°F.

2.0 AIR BEARING PLATFORM

The Air Bearing Platform shown in Figure B-3, when used on the Precision Floor, provides two degrees of translational freedom (X and Y) and one degree of rotational freedom (vehicle yaw).

The platform is supported on three equally spaced air bearing pads. Regulated nitrogen gas is the medium used to float the platform. With a net load of 1,000 lbs, the platform can operate 60-80 minutes without re-supply. Calibration tests have shown the frictional level between the platform and the floor (drag force) to be less than 1 gm (0.04 oz)

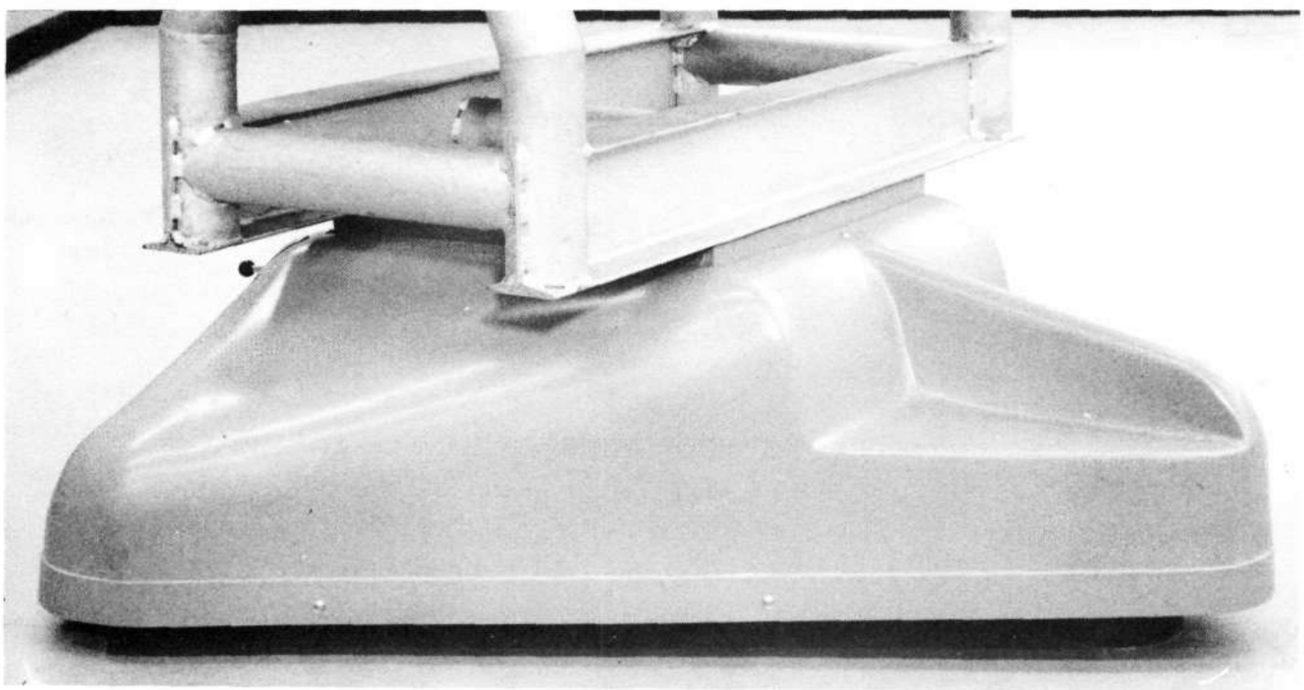


FIGURE B-3 - AIR BEARING PLATFORM

3.0 REMOTE MANEUVERING UNIT (RMU)

The RMU, Figure B-3a, is an unmanned remotely maneuverable unit, which is used as the baseline vehicle in demonstrating the capability and salient characteristics of teleoperators. The experiment program pursued in Phase II combines tasks of maneuvering and docking with those of manipulation to evaluate the overall capability that current state-of-the-art permits and to identify regions requiring further development. The RMU fulfills the maneuvering and docking portion of the objective. When it is equipped with the 12-M manipulators it can perform full task simulation of rendezvous docking and manipulation.

The RMU is a completely self-contained subsatellite with all subsystems necessary to search and acquire a target, stationkeep relative to the target at a selectable range, circumnavigate the target and finally perform a close range rendezvous and docking maneuver. The RMU may be operated in either of two control modes - 1) automatic, and 2) manual. In the automatic mode, the RMU will search acquire and rendezvous with a target using error signals generated by on-board sensors. In the manual mode, the RMU is operated from a remotely located operator's station via RF link, from cues derived by direct observation of the vehicle, or from video displayed on a TV raster. Additional displays to assist the operator include: range, range rate, propellant remaining and battery status.

3.1 Functional Characteristics of Major Subsystems

Characteristics of major RMU subsystems are described in subsequent paragraphs.

3.1.1 Data Link - The uplink utilizes 30 channels for discrete control commands and mode select commands. Channel assignments are shown in Table B-I.

The downlink employs 10 analog channels. Channel assignments, characteristics and accuracy is shown in Table B-II. The downlink transmitter operates on frequency of 27 MHz and has an operational range of 1/4 n. mile.

The video RF downlink is transmitted directly from the camera oscillator. The maximum operational range of the video RF link is limited to 100 ft.

3.1.2 TV Subsystem - The TV constitutes the primary guidance sensor of the RMU. It is used to discern target characteristics in an inspection mission, as well as derive cues for manually controlling the RMU.

The TV camera is rigidly affixed to the RMU structure. It is boresighted along the mean centerline of the vehicle, and is equipeed with remote controls for zoom and focus.

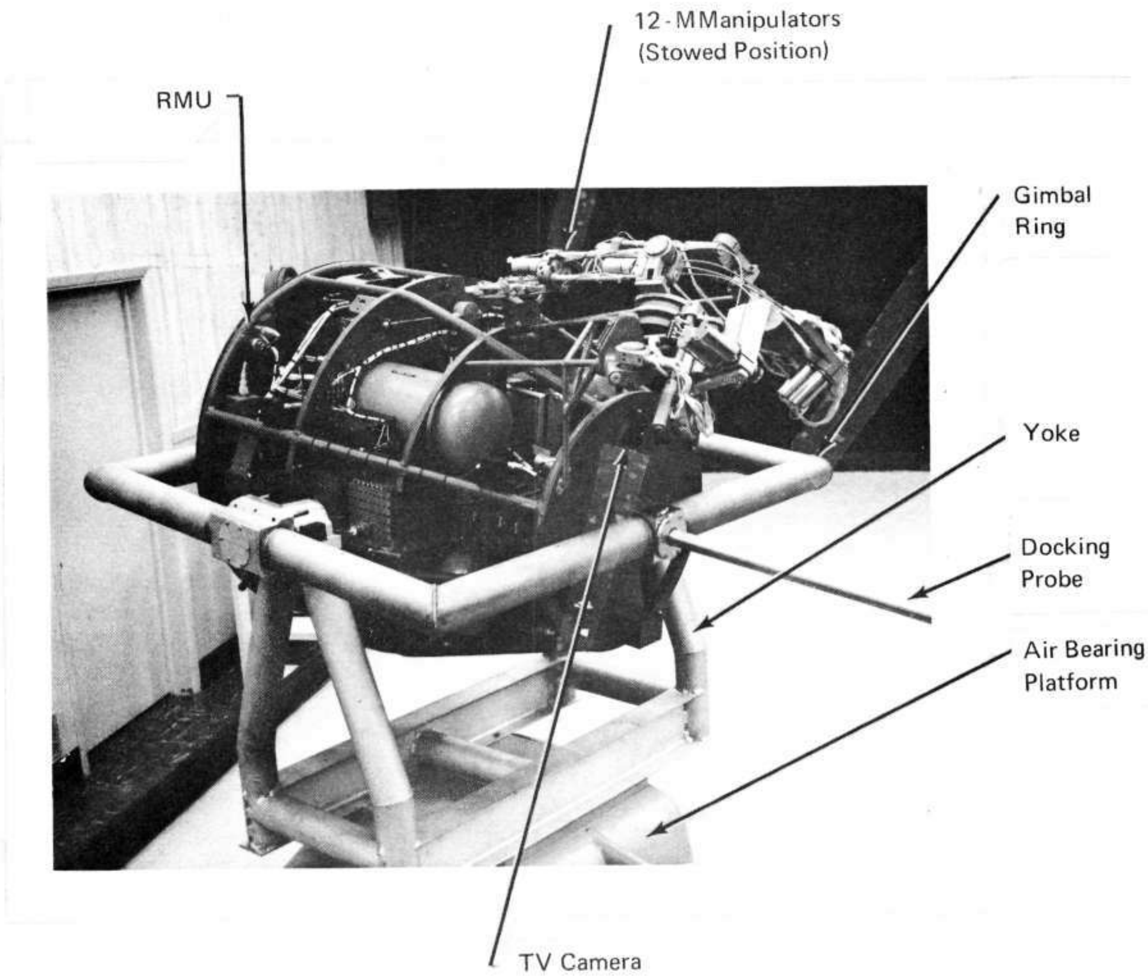


FIGURE B-3A - RMU AND AIR BEARING PLATFORM

Channel	Function	
	Manual Mode	Automatic Mode
1	Pitch up	
2	Pitch down	
3	Roll left	
4	Roll right	
5	Yaw left	
6	Yaw right	
7	+ X translation	Decrease range
8	- X translation	Increase range
9	+ Y translation	
10	- Y translation	
11	Manual	
12	Minimum Impulse	
13	Zoom In	Zoom In
14	Zoom Out	Zoom Out
15	Focus Near	Focus Near
16	Focus Far	Focus Far
17	Jet Activate	Jet Activate
18		Circle Target CCW
19		Circle Target CW
20	Pitch CMG Hi-Rate	
21	Pitch CMG Lo-Rate	
22		Hold Range
23	Roll CMG Hi-Rate	
24	Roll CMG Lo-Rate	
25	Yaw CMG Hi-Rate	
26	Yaw CMG Lo-Rate	
27	Spare	
28	Spare	
29	Spare	
30	Spare	

TABLE B-I - UPLINK CHANNEL ASSIGNMENTS

Channel		Type	Accuracy	Range
No.	Function			
1	Range	Analog	±3%	0 - 10V
2	Range Rate	Analog	±3%	0 - 10V
3	Fuel State	Analog	±3%	0 - 10V
4	Battery Condition	Analog	±3%	0 - 10V
5	Pitch Position	Analog	±3%	0 - 10V
6	Roll Position	Analog	±3%	0 - 10V
7-10	Spare	Analog	±3%	0 - 10V

TABLE B-II - DOWNLINK CHANNEL ASSIGNMENTS

a) Camera Characteristics:

Scanning System	-	Random Interface Scan
Scanning Frequency	-	15.75 KC horizontal; 60 cps vertical
Tube Type	-	Vidicon 7735A
Horizontal Resolution	-	300 lines
Input Power	-	117 VAC ± 10% single phase
Dimensions	-	14 cm (5.5") high x 7.6 cm (3.0") wide x 23.7 cm (9.4") deep

b) Optics:

Relative Aperture	-	f 1.8
Focal Length	-	25 - 100 mm
Zoom Ratio	-	4:1
Focusing Range	-	∞ to 2.5 m (∞ to 8.2 ft)
Lens Mount	-	type 'C'
Lens Head Diameter	-	80 mm.

3.1.3 <u>Stabilization and Control (S&C) Subsystem</u> - This subsystem contains all sensors and electronic circuitry required to detect the target and to generate appropriate error signals to orient the RMU in three degrees of freedom. RMU stabilization may be affected by mass expulsion devices (RCS) or momentum exchange devices (CMG).

a) Translational System - RMU translational is acceleration commandable. The acceleration levels are adjustable. For this program, both longitudinal and transverse accelerations were set to 0.04 ft/sec^2. A minimum impulse bit (100 ms) is provided for translational maneuvers requiring extreme accuracy.

b) Attitude - The RMU attitude may be commanded by acceleration commands (direct thruster firing), or by rate commands. In the acceleration command mode, the angular rate of the vehicle increases for as long as the command persists. Upon removal of the command, the vehicle will continue to rotate at the achieved rate. In the rate command mode, deflection of the control level will accelerate the vehicle until a pre-set rate is achieved. The vehicle will then continue to rotate at this rate for as long as the command persists (lever is deflected). Upon removal of the command (release of control lever) the imparted rate will be removed and the vehicle will boresight on the LOS which was achieved at the instant the command was removed; i.e., overshoot is corrected.

Angular accelerations with the mass expulsion devices are:

Pitch	-	4.3 deg/sec^2 (includes the gimbal ring)
Roll	-	9.7 deg/sec^2
Yaw	-	1.6 deg/sec^2 (includes gimbal ring and platform)

Angular rates are selected by the operator. The available rates, which are selected at the operator's console include: 6 deg/sec for the high rate and 3 deg/sec for the low rate.

Commanded rates may be implemented either by mass expulsion devices or by control moment gyros (CMG). The mode of operations is selectable by appropriate switching on the RMU vehicle. The thruster arrangement is shown in Figure B-4. Thruster logic for this arrangement is shown in Table B-III.

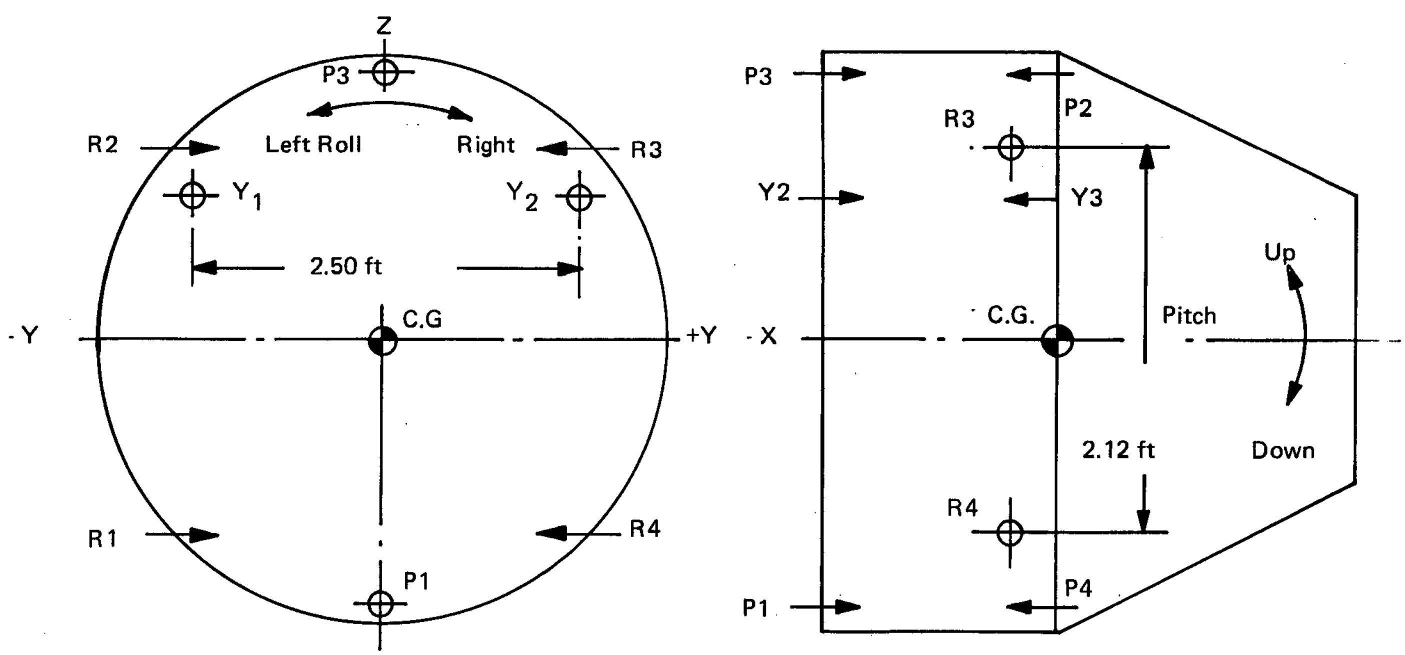


FIGURE B-4 - THRUSTER ARRANGEMENT

BASIC COMMAND	THRUSTERS USED	REACTION MAGNITUDE AND COUPLING		
		PITCH	YAW	ROLL
+X	P1 and P3	2F		
-X	P2 and P4	2F		
+Y	R1 and R2	2F	.8F (R)	
-Y	R3 and R4	2F	.8F (L)	
+Z	R1 and R4	2F		
-Z	R2 and R3	2F		
PITCH (U)	P1 and P2	2.5F		
PITCH (D)	P3 and P4	2.5F		
YAW (R)	Y1 and Y3		2.5F	
YAW (L)	Y2 and Y4		2.5F	
ROLL (R)	R2 and R4			2.0F
ROLL (L)	R1 and R3			2.0F

TABLE B-III - RMU THRUSTER LOGIC

F = Thrust; L = Left; R = Right

Pure couples are applied for all attitude maneuvers. Lateral motion (± Y) couples in yaw because of CG off-set. A block diagram of the attitude and translation control system is shown in Figure B-5.

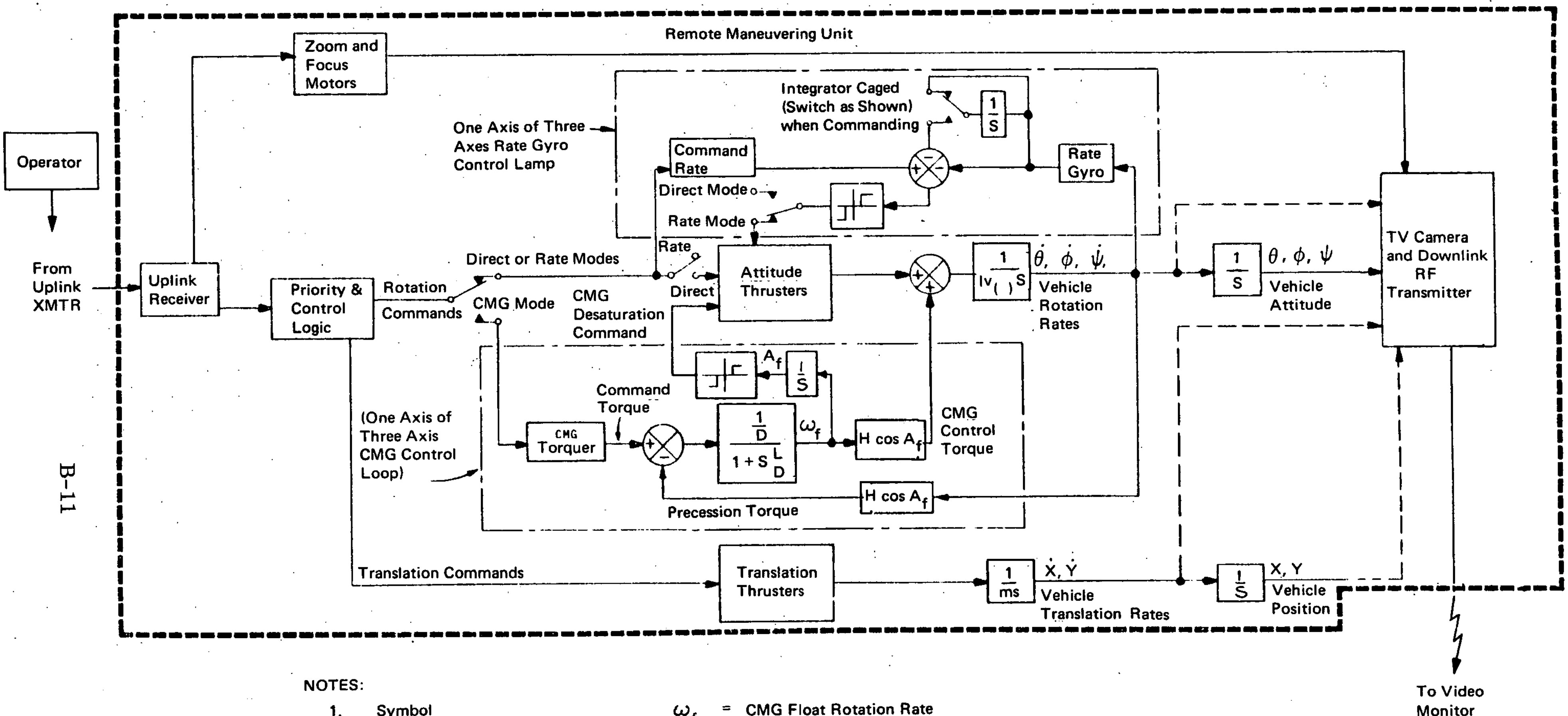
In the automatic mode of control, commands for rendezvous and stationkeeping are generated from error signals originating from on-board sensors. The ranging and boresight circuitry derives range, range rate and angular information and commands the RMU to

a) Acquire and lock-on to a target from an arbitrary initial orientation

b) Translate and rendezvous with the target to a preset range.

c) Stationkeep at a fixed position relative to the target.

d) Circle the target at constant velocity clockwise or counterclockwise while constantly boresighting on it.



NOTES:

1. Symbol

$Iv_{( )}$ = Vehicle Moment of Inertia About ( ) Axis

θ = Roll Angle

ϕ = Pitch Angle

ψ = Yaw Angle

m = Vehicle Mass

D = CMG Damping

I_f = CMG Float Moment of Inertia

ω_f = CMG Float Rotation Rate

A_f = CMG Float Angle

H = CMG Angular Momentum

S = Laplace Operator

2. RMU Priority Logic

Any Combination of Rotation Commands Allowed Simultaneously

Any Combination of Translation Commands Allowed Simultaneously

Any Rotation Command Inhibits All Translation Commands

FIGURE B-5 - ATTITUDE AND TRANSLATION CONTROL SYSTEM

Ranging and boresight information is generated from an IR beam which emanates from the target and rotates at constant RPM.

Figure B-6 is a block diagram of the ranging and orientation circuit and IR detector arrangement used on the RMU.

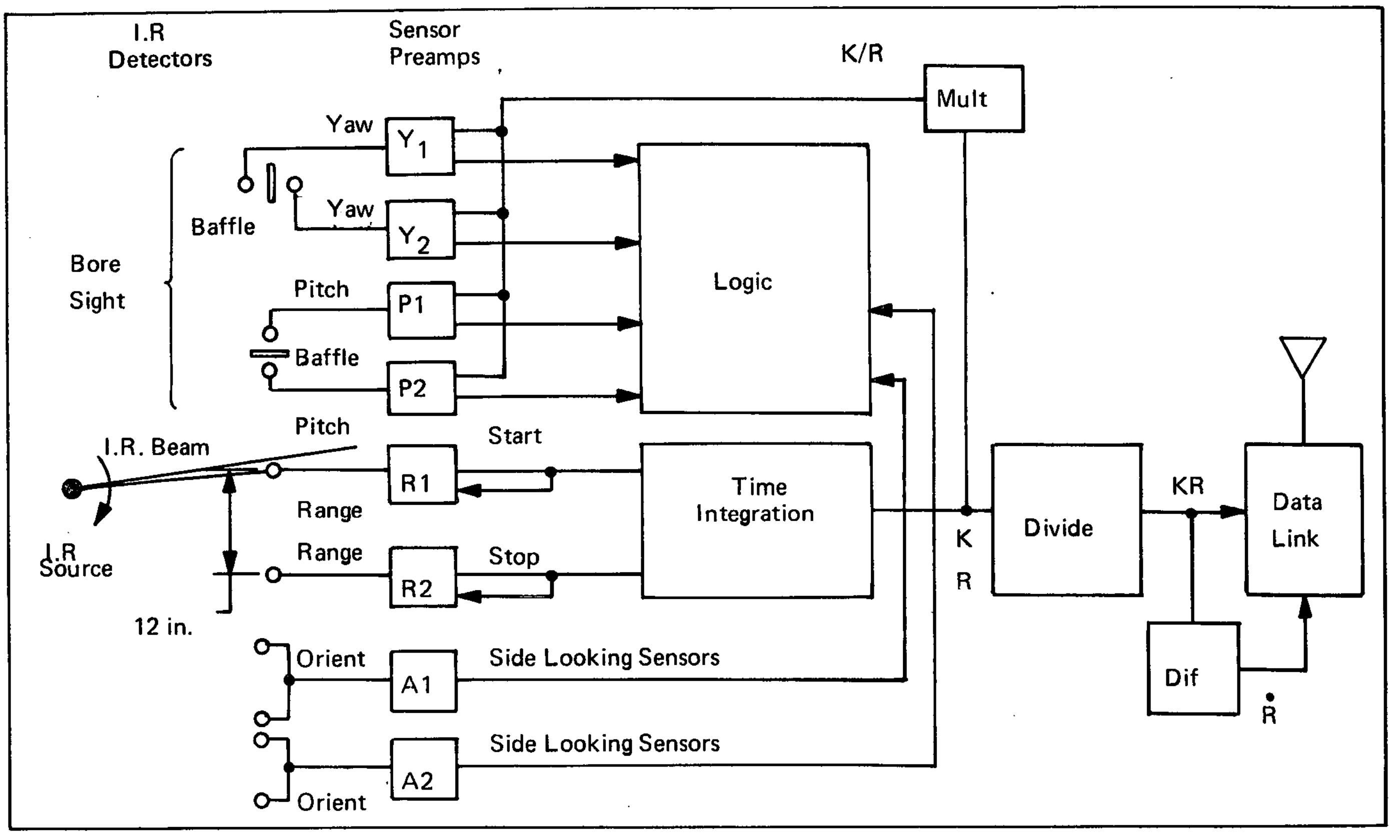


FIGURE B-6 - RANGING AND ORIENTATION SUBSYSTEM BLOCK DIAGRAM

Four IR sensitive strip detectors are used to generate error signals in pitch and yaw for boresighting on the target. The detectors are installed in a masked baffle arrangement. Roll attitude is sensed using a pendulum as a verticality sensor. During the search and acquisition phases, the vehicle roll is nulled first.

Ranging is accomplished by starting and stopping a time integration, again using IR detectors on a fixed baseline. Range to the target is obtained by triangulation; range rate is derived by differentiating the computed range.

Four side-looking sensors and one aft looking sensor are used to generate error signals which orient the vehicle toward the target during search and acquisition maneuvers. The commanded orientation maneuver is based on the minimum angular excursion required to boresight.

3.1.4 Propulsion - The RMU propulsion subsystem, Figure B-7, operates on cold nitrogen gas regulated to the desired chamber pressure from a high storage pressure system. The propulsion subsystem consists of the high pressure storage, regulation and distribution, and twelve thrusters whose arrangement was shown in Figure B-4.

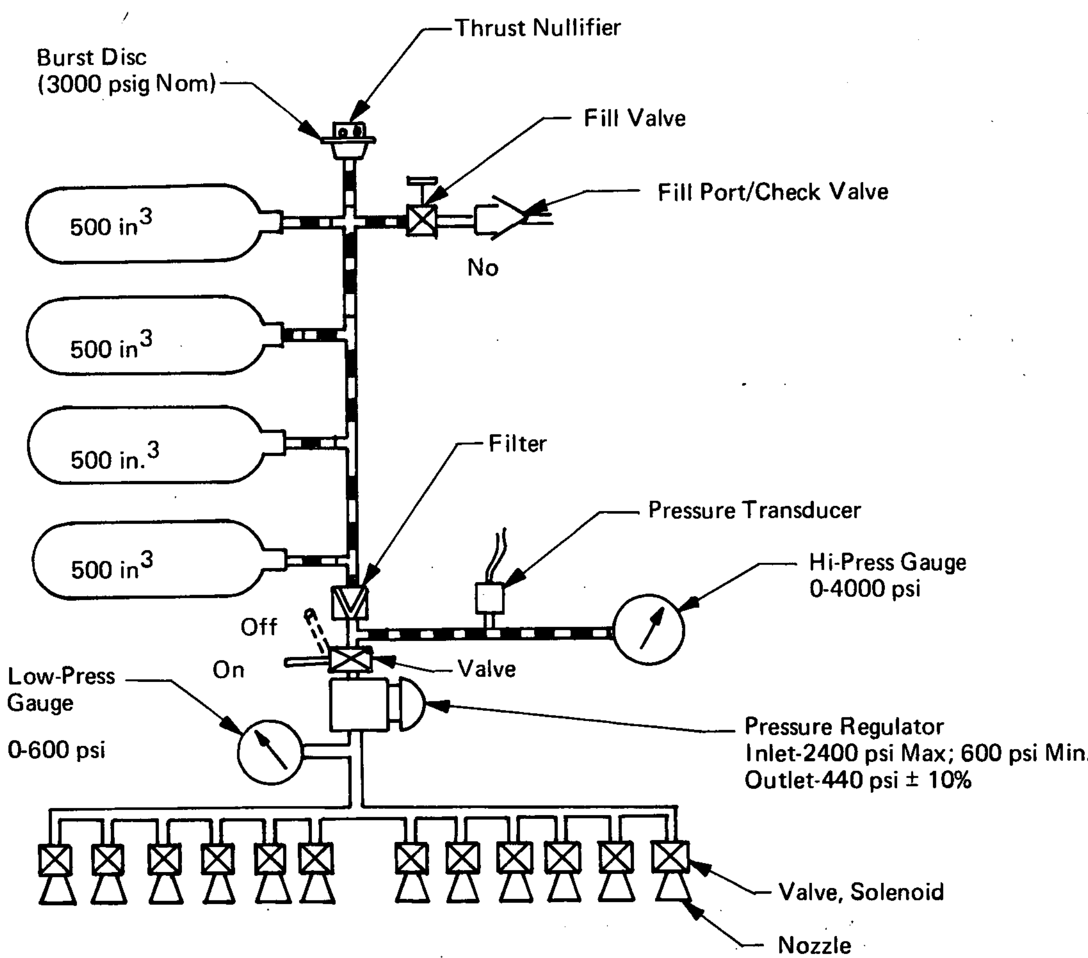


FIGURE B-7 - PROPULSION SYSTEM SCHEMATIC

Primary Performance Characteristics

Propellant	-	Cold N_2 gas
Capacity	-	2000 in^3
Maximum Pressure	-	2400 psig
Number of Thrusters	-	12 (see Figure 2 for arrangement)
Thrust Level	-	.5 to 5 lb_f Incremental thrust variation provided by 3 orificing steps; feed pressure variation within each step provides continuous adjustment.

3.1.5 Power Supply and Electrical Distribution - The RMU provides the power required to drive all electronics, thruster valves, control moment gyros and torquers for a period of 1/2 hour on a typical RMU duty cycle.

The primary source of power is NiCad batteries capable of providing 7.5 amp hours at 28 VDC ±10% based on full discharge within one hour at room temperature.

3.1.6 Manipulators - The 12-M manipulators shown in Figure B-8 represents the latest configuration of arms subjected to evaluation. The 12-M arms are the lightweight version of a more substantial configuration, the 10-M arms. The latter, a dimensionally interchangeable set, were used early in Phase I for interface identification and integration tests.

A truss arrangement was designed and fabricated to provide the interface between the manipulator arms and the RMU in such a way as to minimize limitation to the excursion envelope, yet permit stowage for maneuvering tasks. In this stowed position the RMU is balanced and can be maneuvered without excessive waste of propellants or large cross coupling produced by center-of mass offsets.

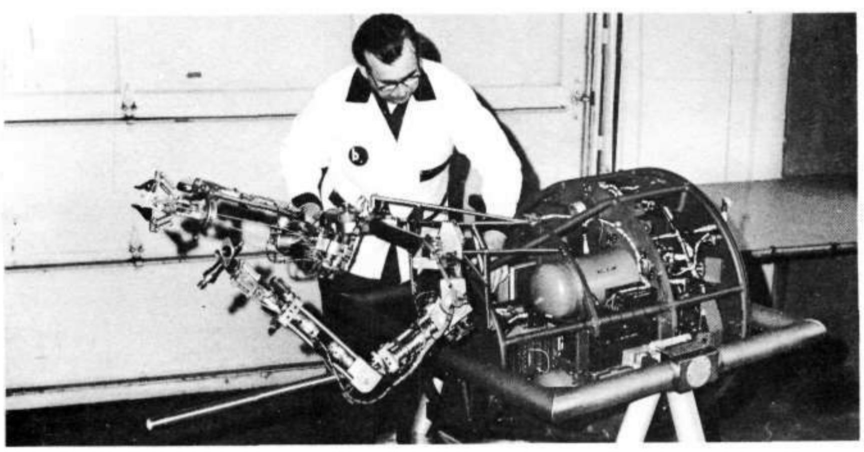


FIGURE B-8 - 12-M MANIPULATOR ARMS

3.1.6.1 Characteristics of the 12-M Manipulator Arms - The 12-M is an anthropomorphically configured manipulator consisting of a right and a left arm. Each arm has seven joints, each providing one degree of freedom, and is driven by a 12 VDC motor with appropriate gear reduction heads. Motors are mounted at or near the joint that they drive with exception of the wrist pitch and hand motors.

In addition to the motor, a potentiometer installed at each joint permits the manipulators to be used in the position command mode (see Para. 6.2 and 6.3).

Envelopes

- Reach when fully extended - 32" from shoulder pivot
- Excursions (installed on the RMU) - These excursions represent the limits that can be obtained with all controllers for performing useful work (not stowage).
  - Up - 70° from local horizontal
  - Down - 90° from local horizontal
  - Left (RT Arm) - 80° from shoulder yaw pivot centerline
  - Right (LT Arm) - 90° from shoulder yaw pivot centerline
  - Left (LT Arm) - 80° from shoulder yaw pivot centerline
  - Right (RT Arm) - 90° from shoulder yaw pivot centerline
- Weight of 12-M manipulator arms - 15 lbs each
- Tip Deflection - 2.2 inches when fully extended at stall torques
- Stall Torques - The torques listed below represent those necessary to stall a joint under most demanding loading conditions maximum extension of the member of the manipulator tested, and so oriented as to counter the maximum gravitational effect. (Results are from tests performed in August 1971 upon receipt of the equipment.)
- Shoulder Pitch - 350 in-lb
  - Yaw - 140 in-lb
  - Roll - 160 in-lb
- Elbow - 180 in-lb
- Wrist Pitch - 5 in-lb (Spring limited)*
  - Roll - 30 in-lb
- Hand (squeeze) - 10 lbs

---

*The wrist pitch drive uses a cable to deflect the wrist in one direction. When the cable tension is relieved the wrist return is accomplished by a spring.

4.0 FLIGHT CONTROL CONSOLE

The flight control console shown in Figure B-9 accommodates displays, controls and all subsystems necessary for remote operation and monitoring of RMU subsystems.

4.1 Displays

The video monitor constitutes the primary display in the Flight Control Console. The view displayed is that seen by RMU body mounted TV camera boresighted along the mean vehicle centerline. Other information displayed on the console includes:

- Range in ft.
- Range Rate in ft/sec
- Propellant remaining in %
- Battery condition in %

4.2 Controls

The horizontal (desk portion) of the Flight Control Console contains all controls for mode select options and for RMU commands.

Commands for RMU control in the manual mode originate in two separate control levers. The left hand controller generates translational commands. The right hand controller generates attitude commands. Lever deflection is in the direction of the desired motion.

4.3 Data Link

The 30 channel command encoder-transmitter uplink and the 10 analog channel receiver-decoder and associated power supplies are contained within the console.

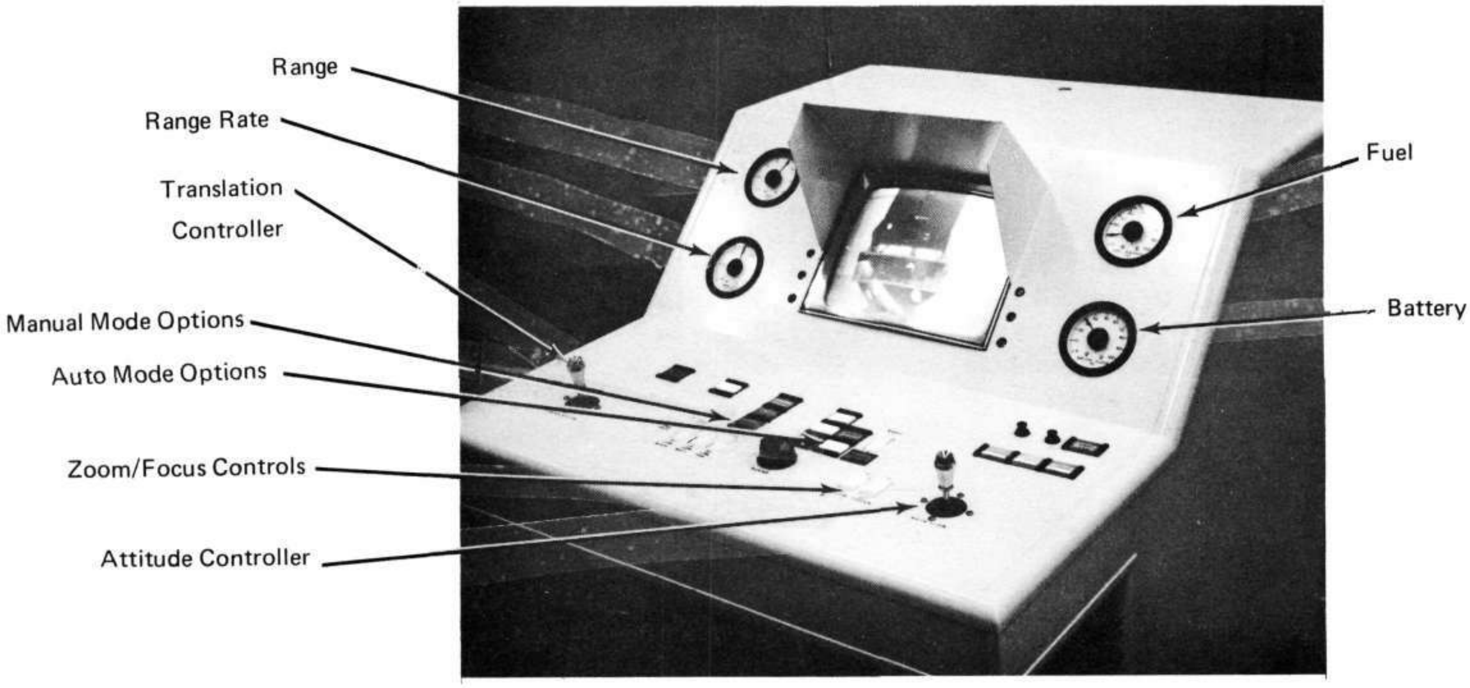


FIGURE B-9. FLIGHT CONTROL CONSOLE

5.0 TASK BOARD FIXTURE

The Task Board Fixture is used to simulate portions of the spacecraft with which the teleoperator will dock to perform predetermined tasks. Figure B-10 shows the task board fixture used throughout the experiment program. As the operator's proficiency improves, the task difficulty should also increase. To permit this change to take place during the experiment program, the task fixture was designed with replaceable inserts representing a mission task or a level of complexity.

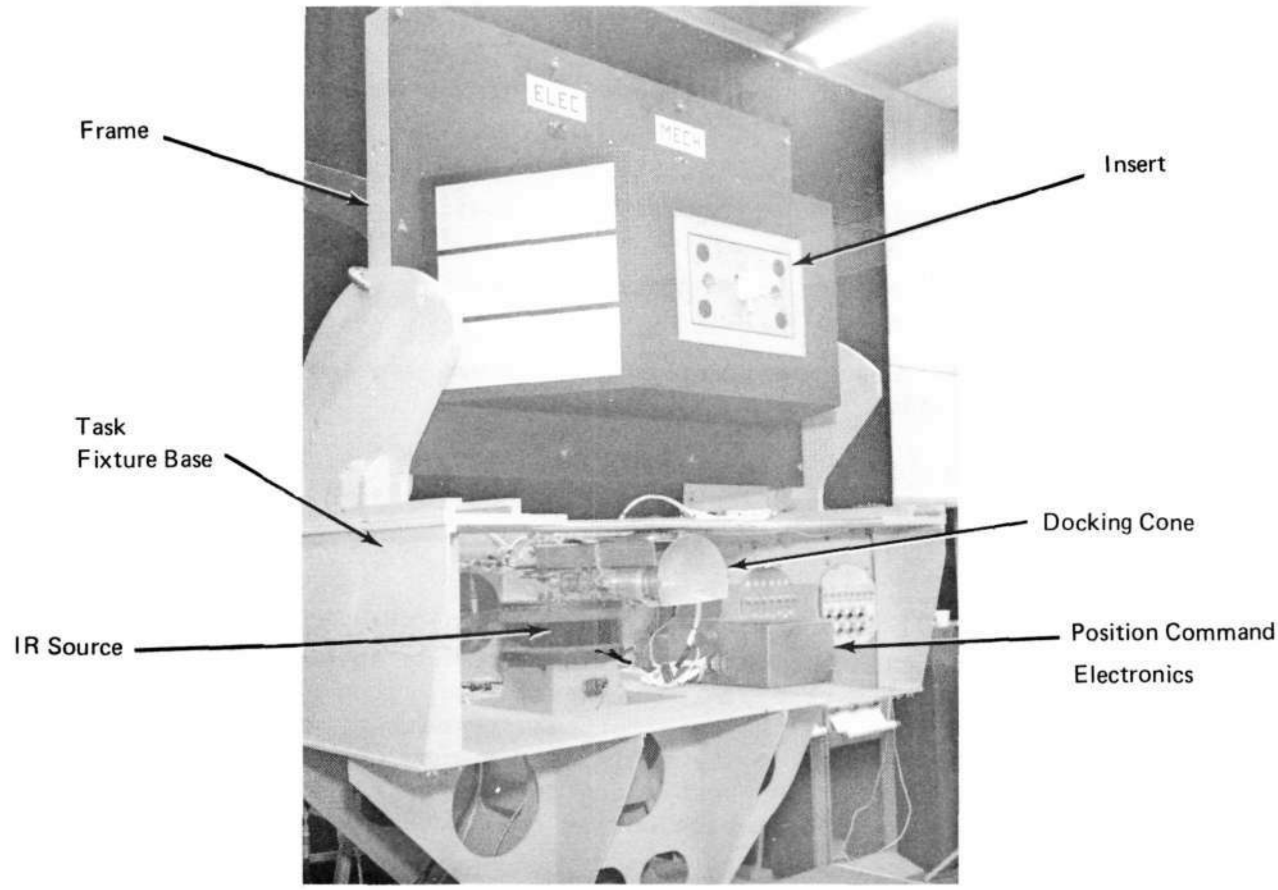


FIGURE B-10 - TASK BOARD FIXTURE

The upper portion of the fixture accommodates a 36 x 47 inch rectangular frame which accepts each of the six different task inserts. The frame inclination may be adjusted from horizontal to vertical in 30 degree increments, and its proximity of the manipulator arms may be varied by as much as 36 inches.

The primary function of the compartment below the movable frame is to properly position the IR source (beacon) and the RMU docking fixture. The forward portion of this compartment should be unobstructed. The space behind the IR source was used to install the following equipment:

- Teleoperator Command Receiver
- Teleoperator Command Decoder, and
- Position Command Electronics

The following sources of power are required at the task board fixture for operation of the manipulator arms and associated equipment:

• 180 psig air or N_2 • 28 VDC" 10%, 2A	For operation of the docking fixture
• + 15 VDC ± 1. %, 5A • - 15 VDC ± 1. %, 5A	Data link Electronics and Position Command Electronics
• + 7 to 12 VDC, 30A • - 7 to 12 VDC, 30A	Manipulator Arms

Power to the above specified tolerances was made available from Bell laboratory equipment.

The IR source isnot in any way associated with the manipulators. It is only necessary for boresighting the RMU and for derivation of range and range-rate information during flight maneuvers.

5.1 <u>Docking Fixture</u>

Manipulation tasks commence after the RMU has docked to the target (Task Board Fixture). The docking fixture closes the structural loop between the work site and the teleoperator, permitting much greater forces and torques to be exerted by the manipulators than would ever be possible in a reaction control or CMG stabilized teleoperator. This approach also eliminates propellant consumption during the conduct of a manipulation task.

The docking fixture also compensates the initial position and attitude misalignments of the RMU and secures the RMU to the work site at a position and attitude suitable for manipulation.

The docking fixture is pivoted to the task board. This pivot swivels about a vertical axis to compensate misalignments in both lateral displacement and RMU attitude (yaw) at the instant contact is made, provided the RMU probe strikes any portion of the docking cone.

A schematic presentation of the docking fixture, identifying its major elements and showing the limits of misalignment it was designed to accommodate is shown in Figure B-11.

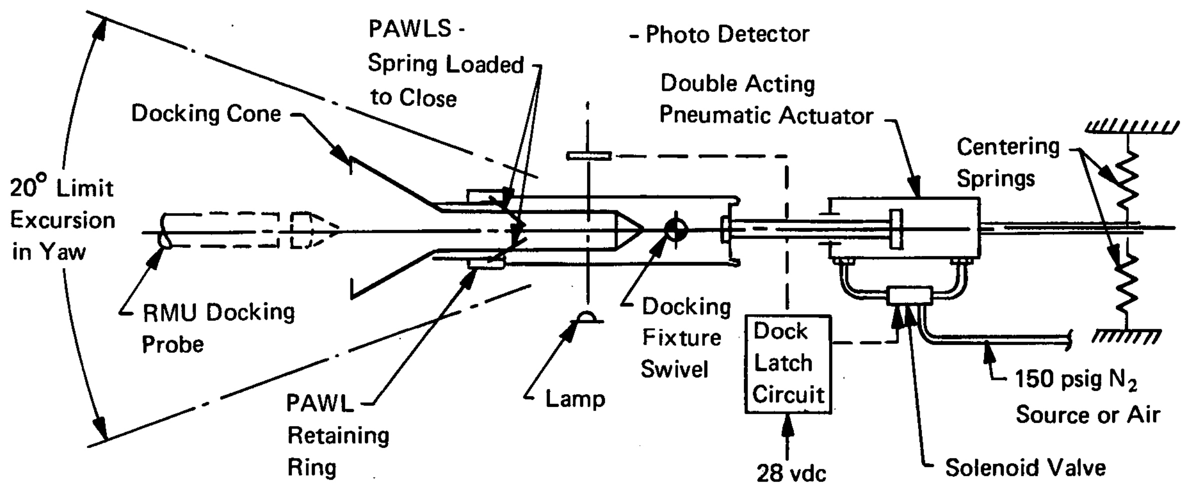


FIGURE B-11 - SCHEMATIC PRESENTATION OF DOCKING FIXTURE

5.2 Principle of Operation - The docking fixture uses a hybrid electrical-pneumatic system to arrest and secure the RMU to the task board. When the RMU probe contacts any portion of the docking cone, due to lateral or angular misalignment the entire docking fixture will rotate to accommodate this misalignment and to guide the probe to the center. Residual velocity of $\sim$ .1 fps is sufficient to complete the docking, however, in the absence of residual forward velocity the probe may be engaged by thruster firing. This action assures, 1) probe engagement into the spring-loaded pawls, and 2) the interruption of the light beam impinging on the photo detector. The absence of the photo detector signal output energizes the solenoid valve to pressurize chamber "A" of the double acting pneumatic actuator, and pulls the RMU until the probe is seated. The pyramid shaped tip of the probe aligns the RMU in roll and locks it in that position until all manipulation tasks are completed. The signal to release the pawls originates at the console and the RMU backs out of the docking fixture using retro-thrust. At the completion of this cycle, the dock fixture is reset and ready for the next docking maneuver.

6.0 CONTROLLERS

One of the primary experimental program objectives is the evaluation of three types of controllers to command and control the 12-M anthropomorphic manipulators. These controllers which varied widely in configuration as well as in control mode include:

- An anthropomorphic exoskeleton (master) controller
- A switch controller, and
- Lever (joy-stick) controllers.

6.1 Anthropomorphic Exoskeleton*

6.1.1 Configuration - This controller, frequently referred to as "master" controller, is shown in Figure B-12. It is configured to fit over the operator's arms with appropriate linkage adjustments. Each controller is capable of generating seven commands, one for each joint of the manipulator.

The seven joints listed in Table B-IV generate commands for motions which correspond to, but do not necessarily cover the full range of excursion envelopes possible with the human arm. The motions, however, are sufficient to yield hemispherical coverage forward of a vertical plane passing through the mounting surface. A potentiometer in each joint generates the command signal for driving the corresponding joint on the manipulator.

JOINT	TYPE OF MOTION
1. Shoulder Pitch	Hinge
2. Shoulder Yaw	Hinge
3. Shoulder Roll	Swivel
4. Elbow (Pitch)	Hinge
5. Wrist Pitch	Hinge
6. Wrist Roll	Swivel
7. Hand	Pentograph

TABLE B-IV - JOINT IDENTIFICATION AND TYPE OF MOTION GENERATED BY THE ANTHROPOMETRIC CONTROLLER

*Controller Designed and Fabricated by Rancho Los Amigos Hospital, Inc. and Furnished to Bell Aerospace as GFE.

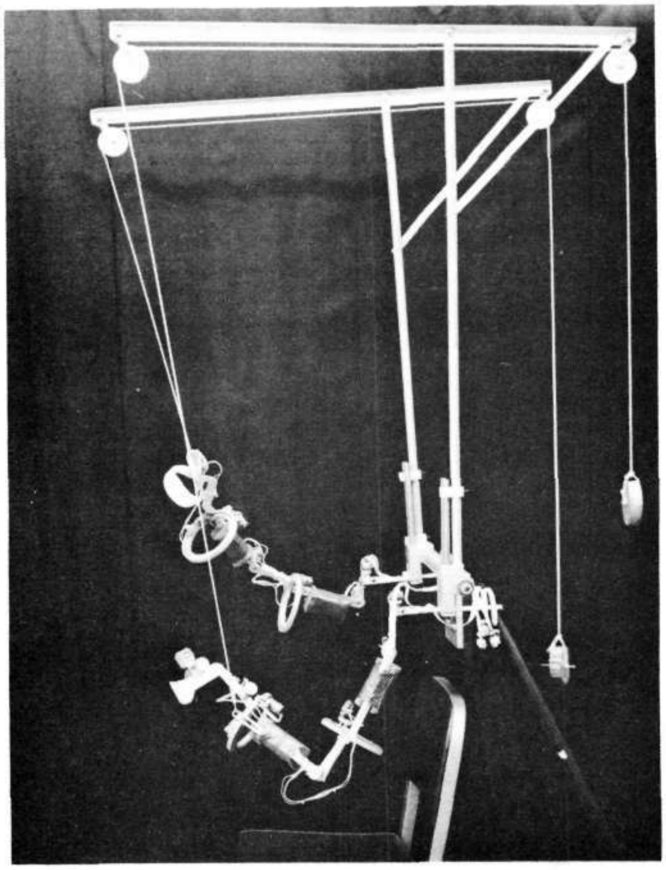


FIGURE B-12 - ANTHROPOMORPHIC EXOSKELETON (MASTER) CONTROLLER

6.1.2 Control System - The Master controller employs a position command system, with appropriate dead bands to modulate the commanded rate and to yield accurate positioning of the end effector (hand). This proportional control results which operates in the following manner:

1. The master and slave potentiometer signals (for corresponding joints) are summed to give error signal.

2. The manipulator motor is driven at its maximum rate in the direction to decrease the error to the threshold.

3. When the error is within this deadband, the sensitivity is changed to the second threshold (approximately 20 mv) and the manipulator motors are operated in the pulsed mode into the final dead band, and the process stops until a new error is supplied by changing the position of the master potentiometer. See Figure B-13.

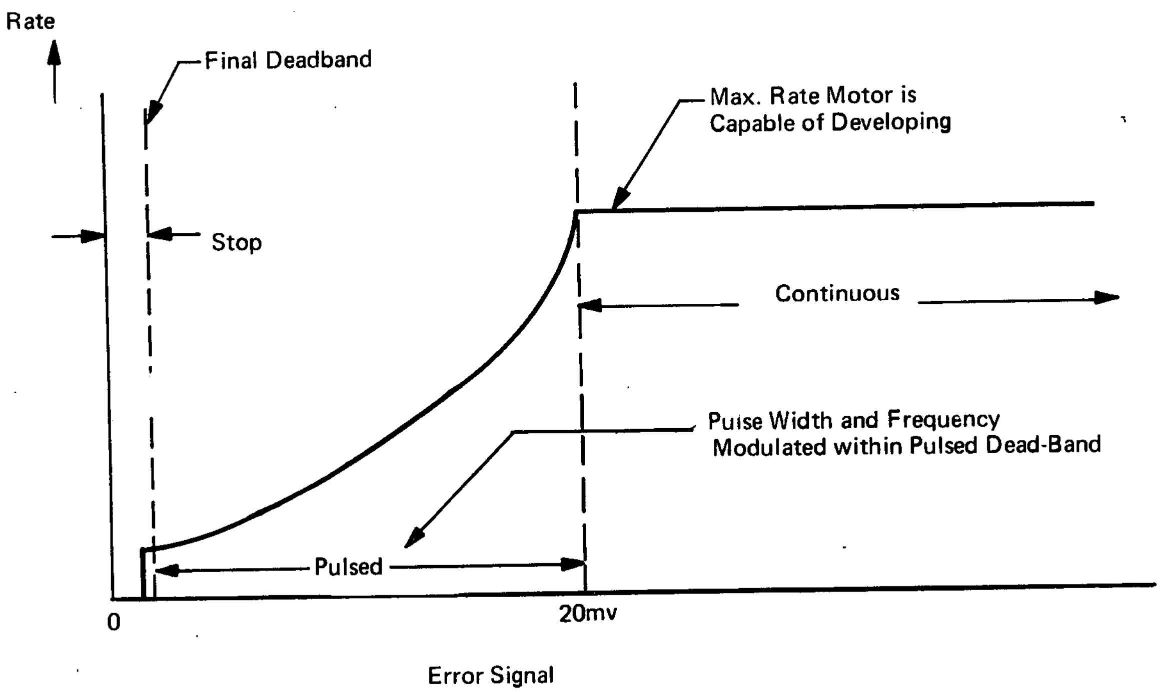


FIGURE B-13 - PROPORTIONAL CONTROL SYSTEM DEADBAND

6.2 Switch Controller

6.2.1 Configuration - The simplest and most compact controller submitted for evaluation was the switch controller. It consists of a control box with two banks of switches. The switches have a center "OFF" position and momentary "ON" position on either extreme. The final configuration of this controller is shown in Figure B-14. It was redesigned from its original configuration to:

1) Arrange the switches in order to provide the correct analogy between switch positions and manipulator joint positions, i.e., switches further away from the operator on the box, controlling the joint furthest away on the manipulator arm.

2) Combine the shoulder pitch and yaw commands into a single double acting switch with proper orientation, and

3) Orient the switches such that deflections of the toggles correspond to the direction of the desired (to the extent possible) motion of the respective manipulator link.

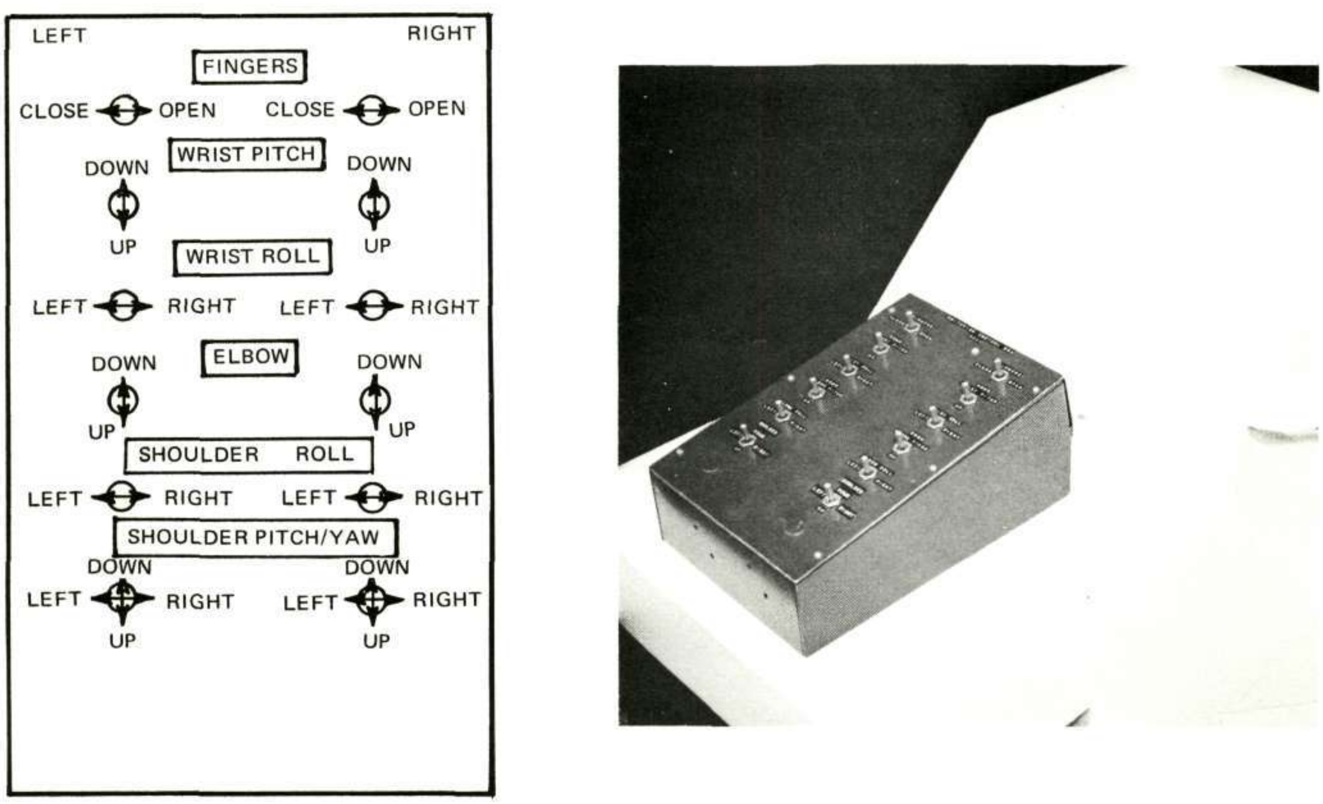


FIGURE B-14 - SWITCH CONTROLLER

6.2.2 Control System - This is a direct system where each switch, when energized, drives a joint on the manipulator at its maximum developed rate. The rate at which each joint is driven depends upon

1. The supply voltage - at which the manipulator motors are driven (it may be varied at the source between 7 and 12 volts)

2. The gear reduction of the motor gear-head, and

3. The load imposed on the joint

When a switch is energized the corresponding joint in the manipulator will achieve and be driven at that rate for as long as the command persists.

The capability to simultaneously drive all joints exists from the control point of view, although its implementation is limited by the operator's inability to actuate so many switches.

6.3 Lever (Joy-Stick) Controller *

6.3.1 Configuration - Two "joy-stick" controllers and associated rate and position control electronics comprise the thid controller subjected to evaluation. The controller shown in Figure B-15 combines the attributes of a position commanding translation system with those of a rate commandable rotational system. The control system consists of the drive linkage, the control handle and the position and rate control electronics.

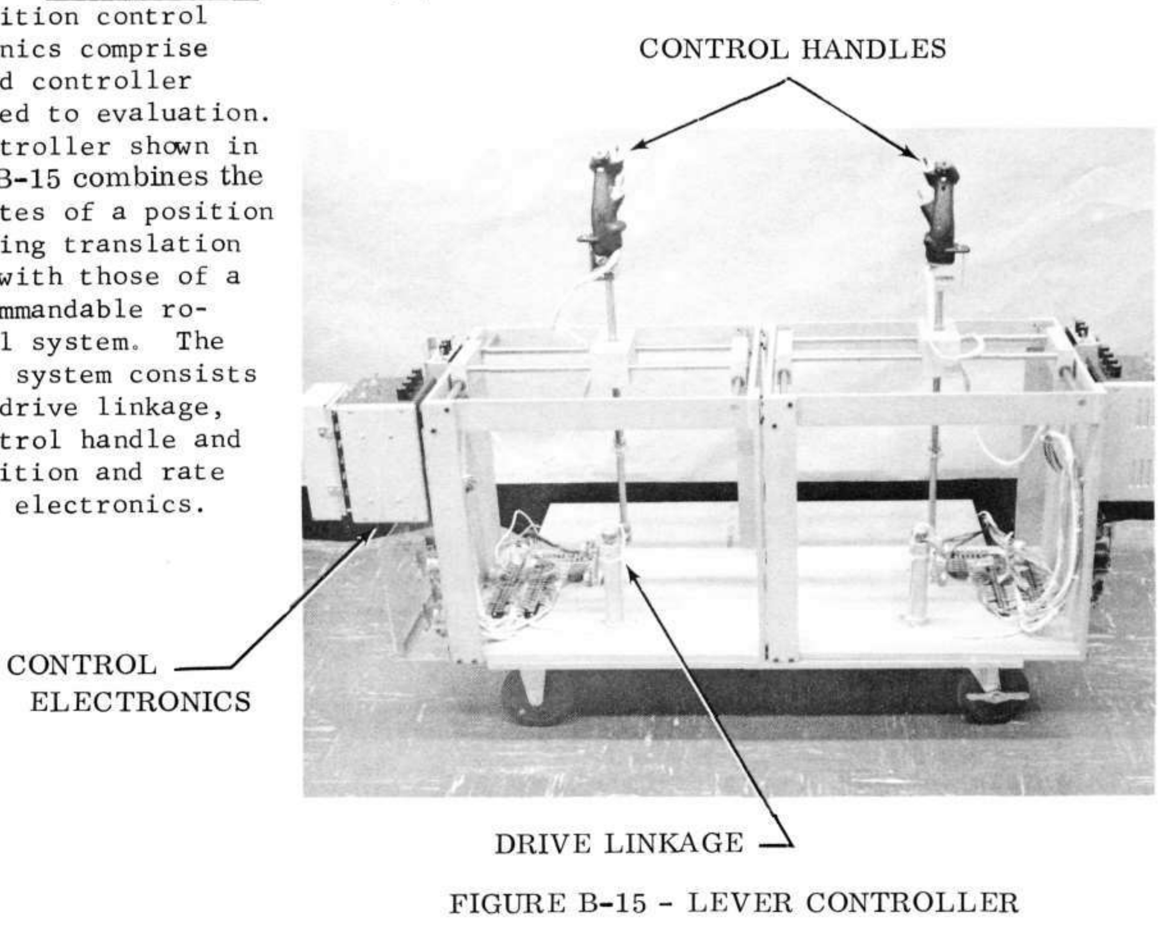


FIGURE B-15 - LEVER CONTROLLER

*Controller Designed and Fabricated by Rancho Los Amigos Hospital, Inc. and Furnished to Bell Aerospace as GFE.

The Drive linkage is a mechanical analog which resolves and sums the components of angular displacements of a four-bar linkage into x-y and z coordinates. The four-bar linkage shown in Figure B-16, is a scaled version of the corresponding linkage used on the manipulator arms.

6.3.2 <u>Control System</u> - Two control modes are used in the lever controller. The translational system, mechanical analog, commands position in the manner similar to the previously described Master controller (Para. 6.1). However, only three joints are so controlled - shoulder pitch, shoulder yaw and elbow. The remaining joints are rate commandable. Direction of rotation is selected with a switch on the control handle. Rate is proportional to the pressure applied to the trigger which controls the rate between 0 and 100%. Releasing the trigger dynamically brakes the driven motors. As many as four joints may be simultaneously operated but the rate of all simultaneously commanded joints is then controlled by the same trigger. This does not imply that all joints are driven at the same angular rate but rather that each joint is driven at approximately the percentage of its maximum capability.

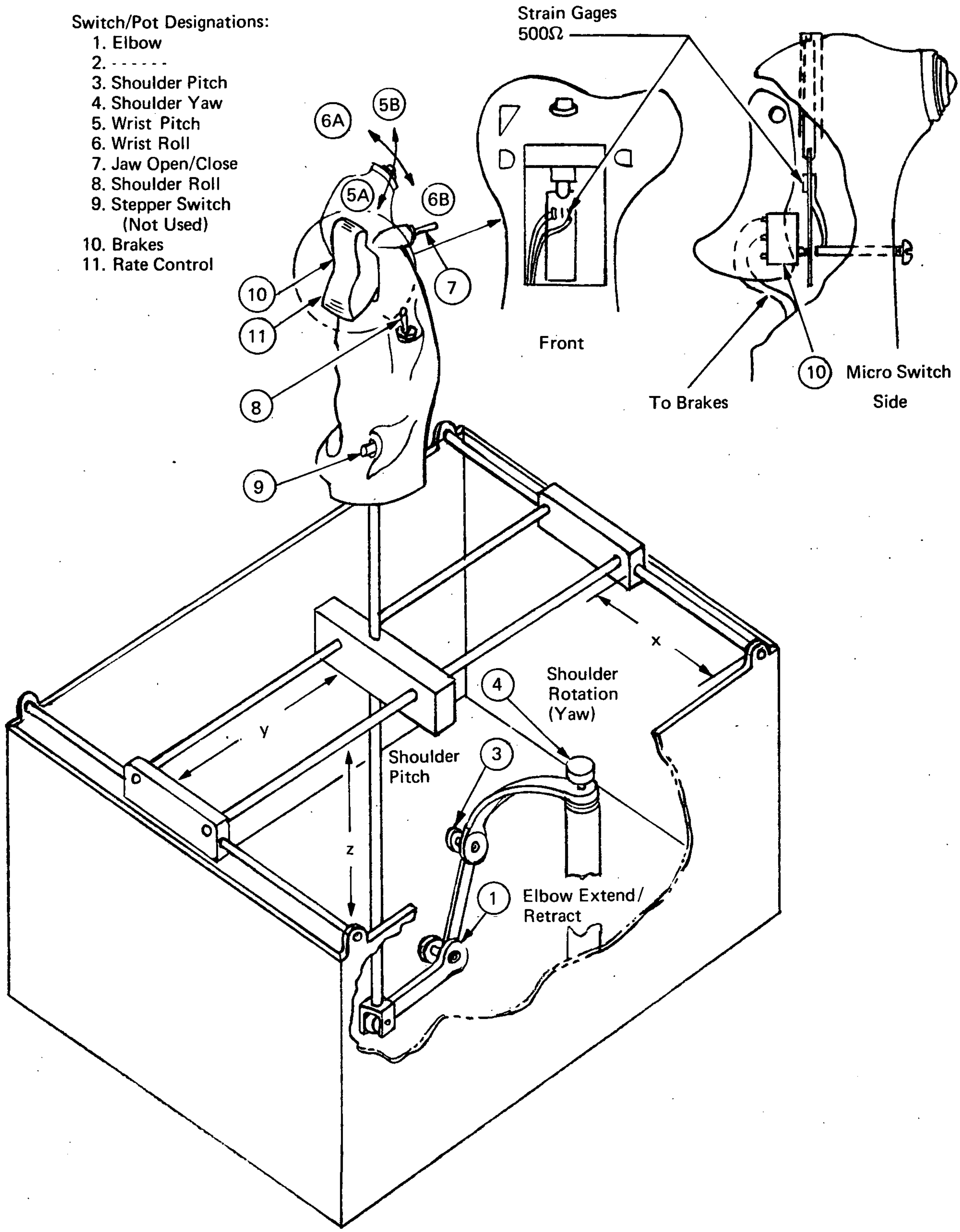


FIGURE B-16 THE LEVER CONTROLLER

7.0 DISPLAYS

The displays used in the experiment program consist of two closed circuit TV systems. Camera positions were varied in each experiment to display orthogonal or oblique views to the operator.

The primary system consists of the following equipment.

1. A high resolution vidicon camera - 945 line Cohu model 2001-099.

2. Zoom lens 17-68 mm focus f 2.2 - 4X, 28° FOV Angenieux Model L2.

3. A high resolution TV monitor, 14 inch, 945 line Conrac Model COF 14/945.

4. Pan and tilt unit for the camera, remotely controlled Cohu Model PT-550-M.

5. Control unit - incorporates controller for pan and tilt commands for the PT-550-M. Cohu Model #8395-6 and associated cables.

6. A camera stand which permitted height adjustment for the camera.

The secondary system consists of the following equipment.

1. A commercial grade Vidicon Camera - 525 line Concord Model MTC-12.

2. Zoom Lens - 17-68 mm focus; f 2.2 - 4X 28° FOV Angenieux Model L2.

3. A commercial grade monitor, 12 inch, 525 line Concord Model MR-700.

4. A camera stand with manual pan and tilt controls.

The primary system was always used in experiments requiring zoom, focus and remote camera pan control. The secondary system was manually positioned and adjusted as dictated by the experiment procedure.

PART II. GUIDELINES FOR THE USE OF EQUIPMENT

1.0 Interfaces of Manipulation Subsystems

Commands for manipulation originating at the Switch Box or the Master controller are transmitted to the Task board via RF link. The commands are received, decoded, and either directly applied to the manipulator as on-off signals as in the case of the switches, or processed through the electronics to command position if they originate at the Master controller.

Commands originating at the lever controller, are processed through a separate set of position/rate control electronics and are then applied to the manipulator via hard-wire connection bypassing the data link.

The block diagram in Figure B-17 shows the interfaces among equipment used for manipulation.

Hard wire connections between the Task board fixture and the RMU may contrast the need for a data link between the control console and the task board. However, closer scrutiny will reveal that elimination of the hard wire connection between the RMU and the task board fixture necessitates installation of all equipment contained in the task board base, and the ±7 to ±12 VDC 30 amp power supply on the RMU. The latter alone, which is needed to drive the manipulator arms, weighs 240 lbs and occupies three cubic feet of space.

The alternative, to use lead-acid batteries results in similar weight penalties to the RMU, and in addition increases down time and does not provide voltage regulation which is considered essential in the evaluation of manipulator performance.

2.0 Miscellaneous Ground Rules -

The following ground rules were adhered to in the operation of the equipment described in preceding sections of this report to ensure equipment compatibility and trouble free operation.

1. The RMU vehicle was hard docked to the task board before manipulation tasks are initiated. Hard docking closes the structural loop between the task board and the RMU and permits the transmission of power and torques from the manipulator to the work site. Secondly, it eliminates the need for dynamic counterbalance to counter the center of gravity offset imposed by extension or retraction of the manipulator arm(s).

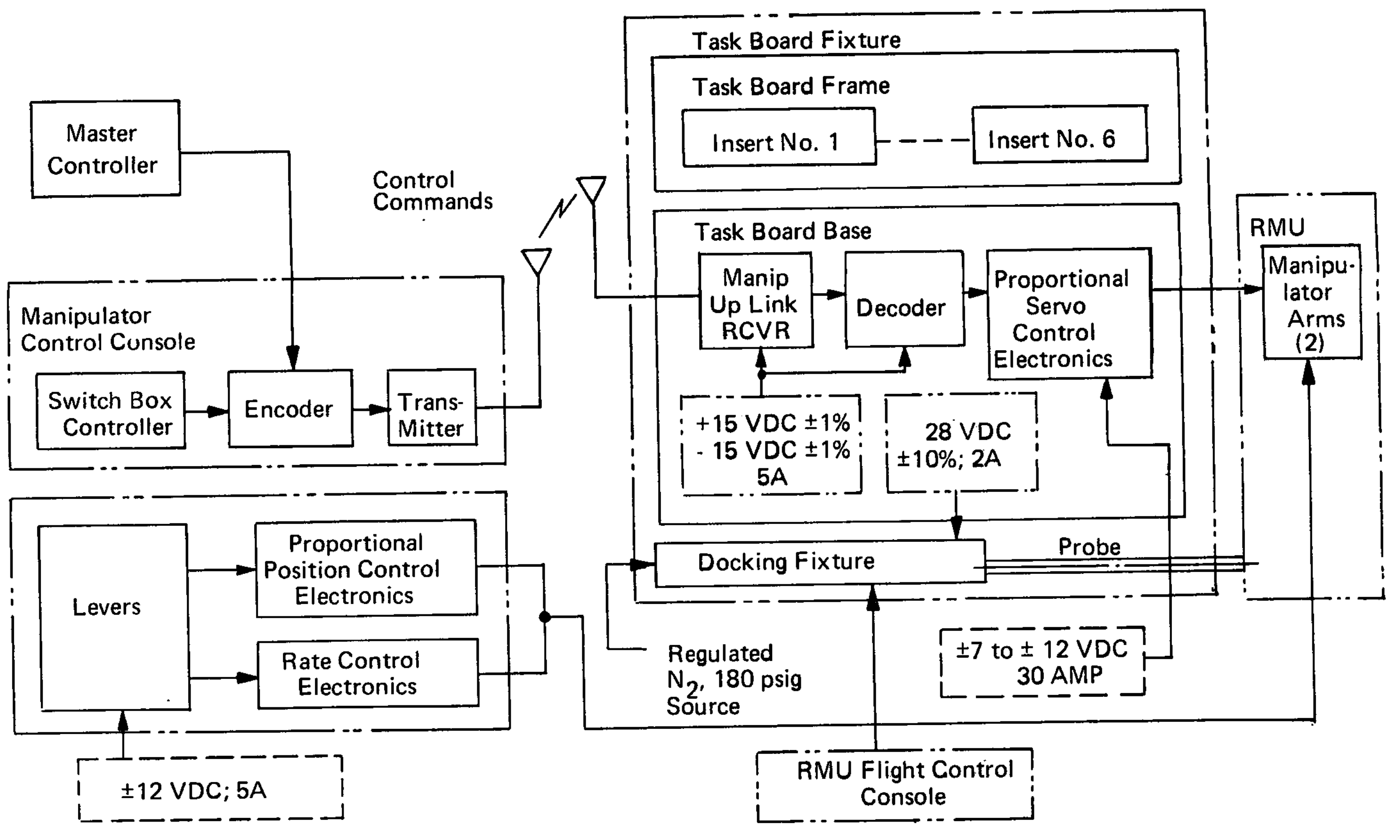


FIGURE B-17 - INTERFACES OF EQUIPMENT USED FOR MANIPULATION

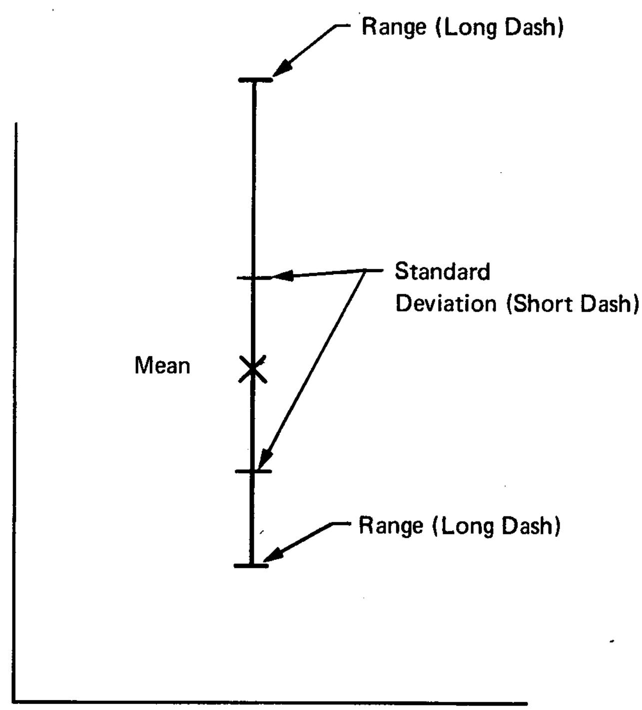
2. The RMU data links (command and data) will not be operated simultaneously with the manipulator data links. Simultaneous operation of the RMU and manipulator command and data links would cause RF interference, since both operate on the same frequency.

3. Closed circuit TV will be used in the manipulator displays. There are three TV displays which could be simultaneously operated. Bandwidth considerations and the cost associated with the design and fabrication of such equipment is not consistent with cost considerations and the end objectives of this program.

APPENDIX C
GRAPHIC DATA ON MANEUVERING AND DOCKING

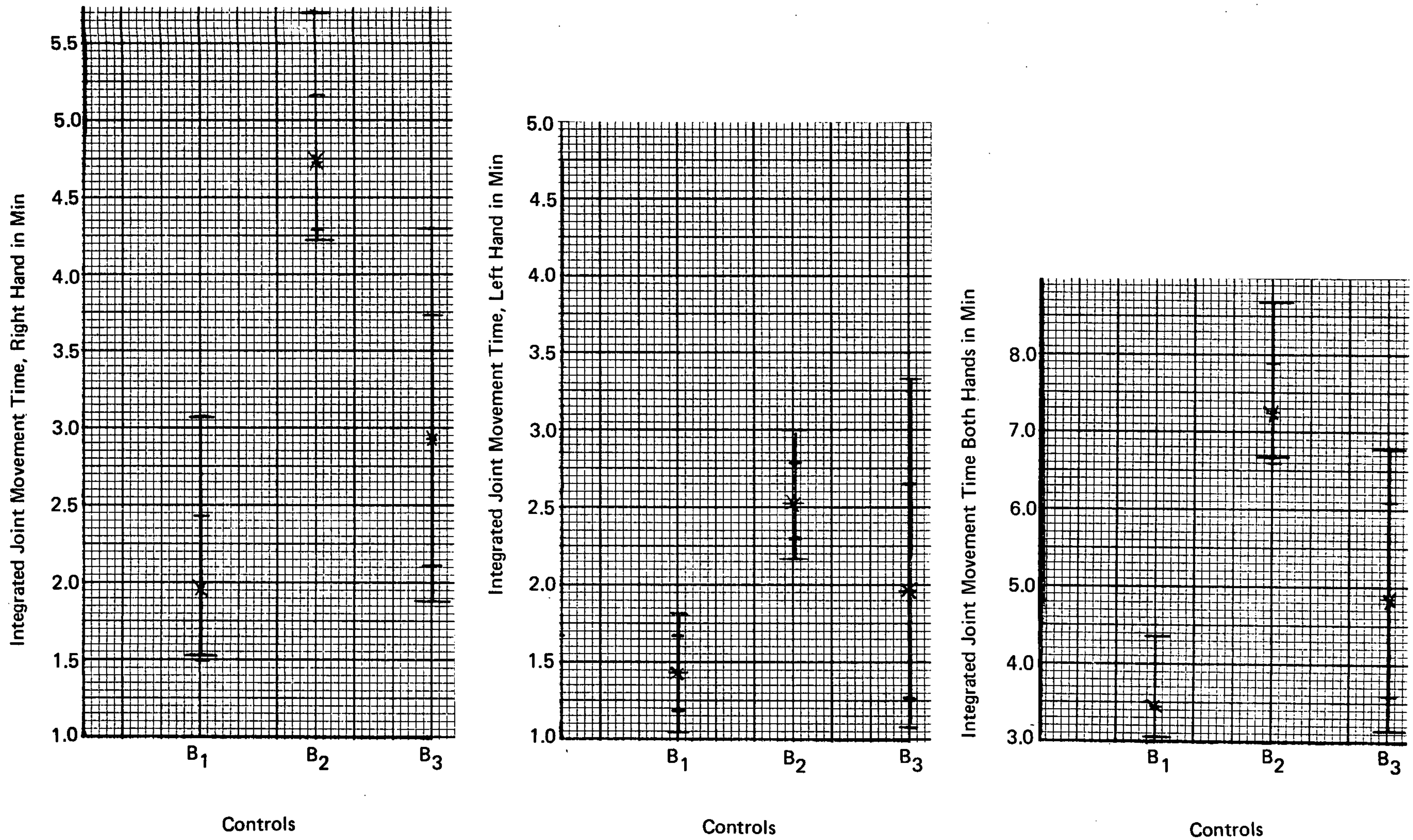
This appendix contains graphical presentations of all the results of manipulation and maneuvering and docking experiments which were identified as being statistically significant using analysis of variance techniques.

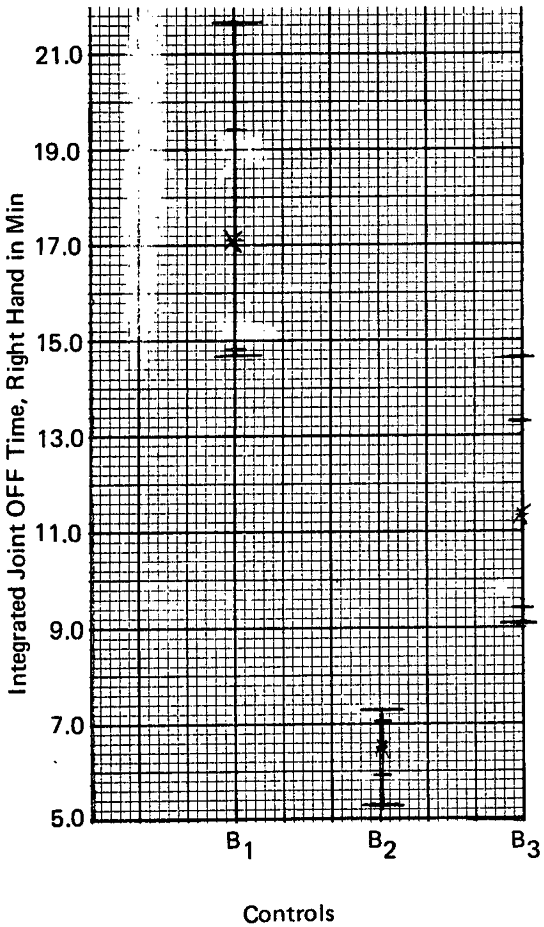
The following code applies to all figures included in this appendix.



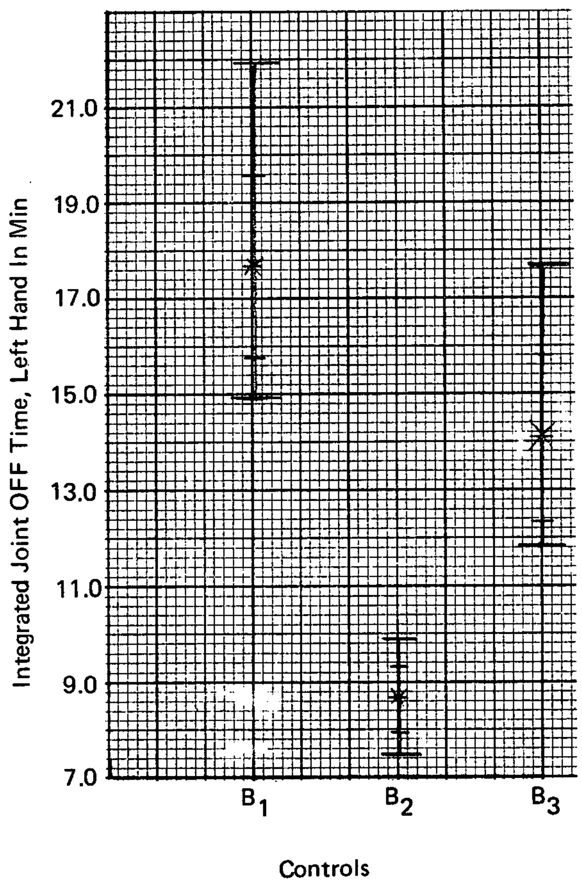
MANIPULATION EXPERIMENT E1: THRUSTER REPLACEMENT

GRAPHICAL PRESENTATION OF
SIGNIFICANT RESULTS

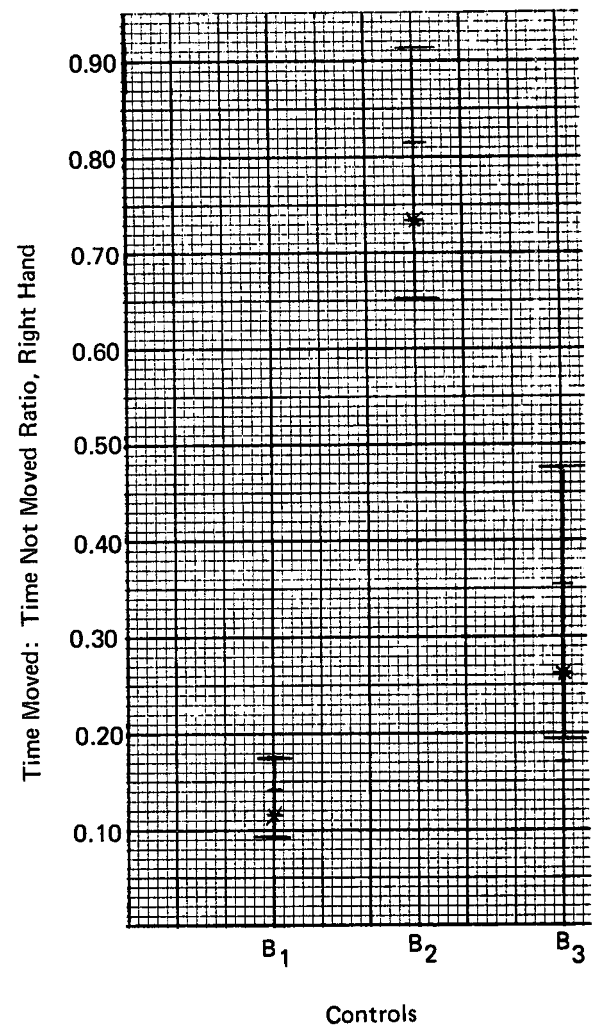

Integrated Joint Movement Time, Right Hand in Min
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
B_1
B_2
B_3
Controls
Integrated Joint Movement Time, Left Hand in Min
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
B_1
B_2
B_3
Controls
Integrated Joint Movement Time Both Hands in Min
8.0
7.0
6.0
5.0
4.0
3.0
B_1
B_2
B_3
Controls



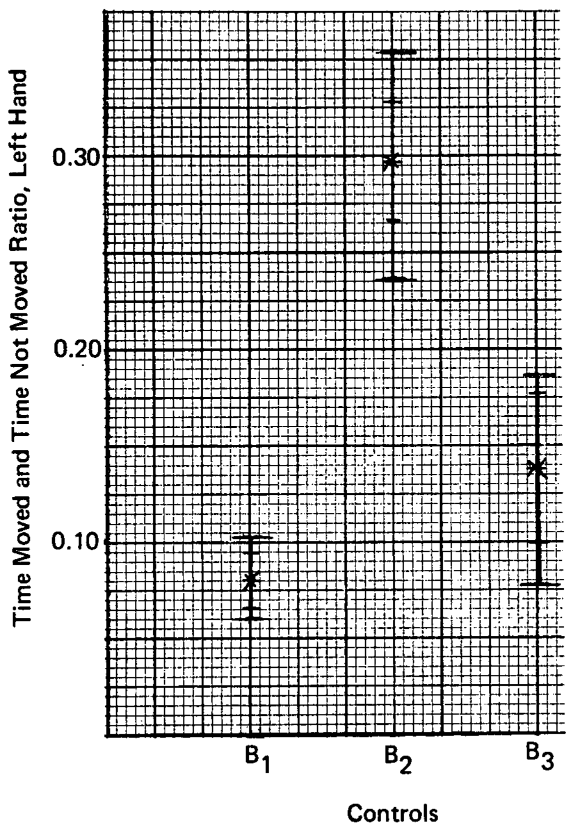
Integrated Joint OFF Time, Right Hand in Min
21.0
19.0
17.0
15.0
13.0
11.0
9.0
7.0
5.0
B_1
B_2
B_3
Controls

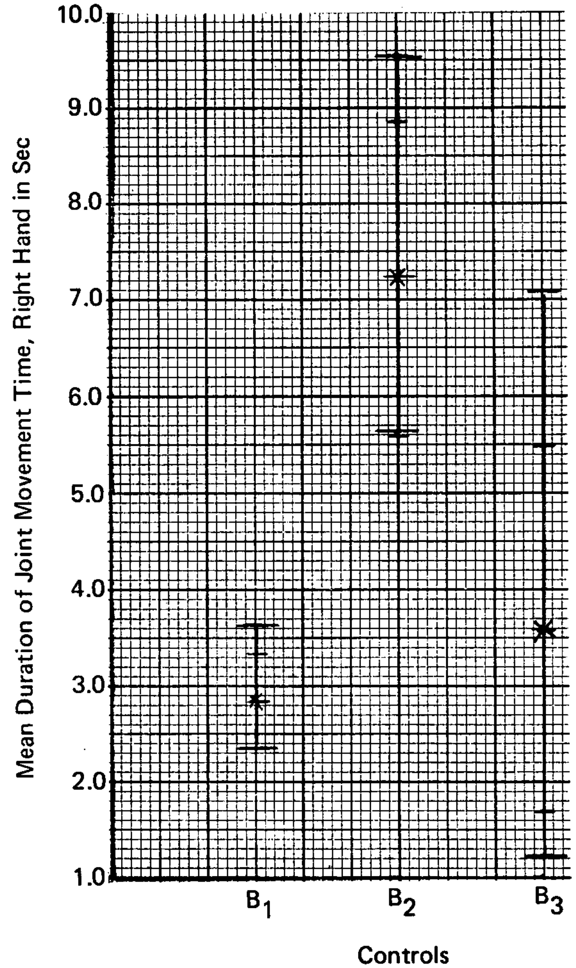


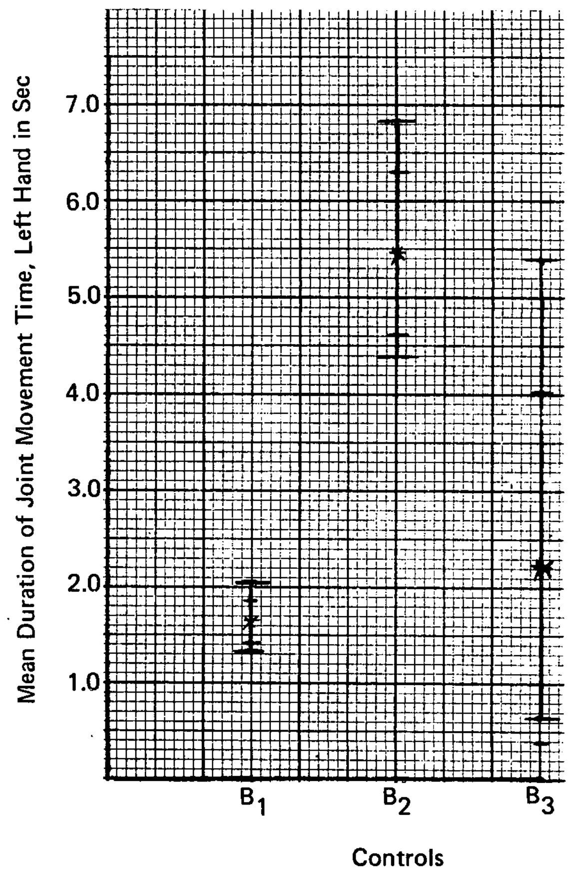
Integrated Joint OFF Time, Left Hand In Min
21.0
19.0
17.0
15.0
13.0
11.0
9.0
7.0
B_1
B_2
B_3
Controls

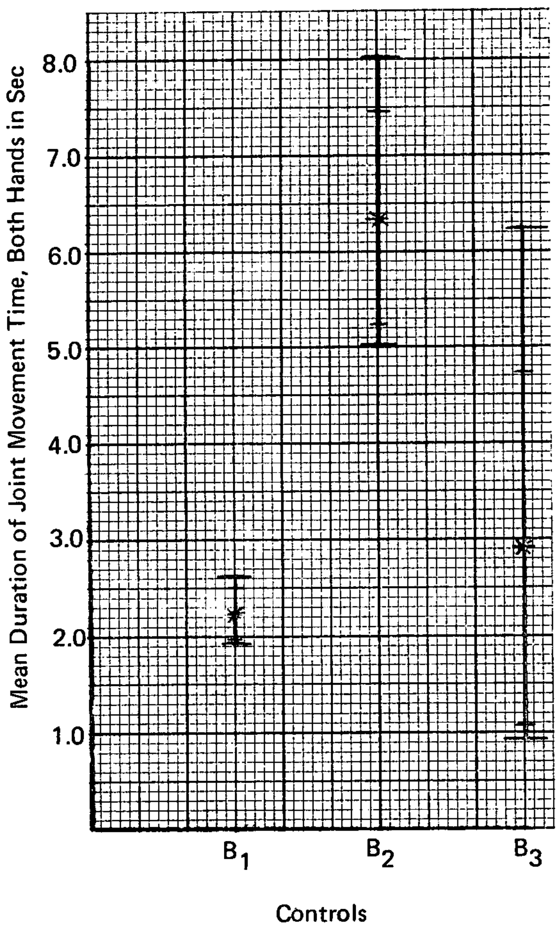


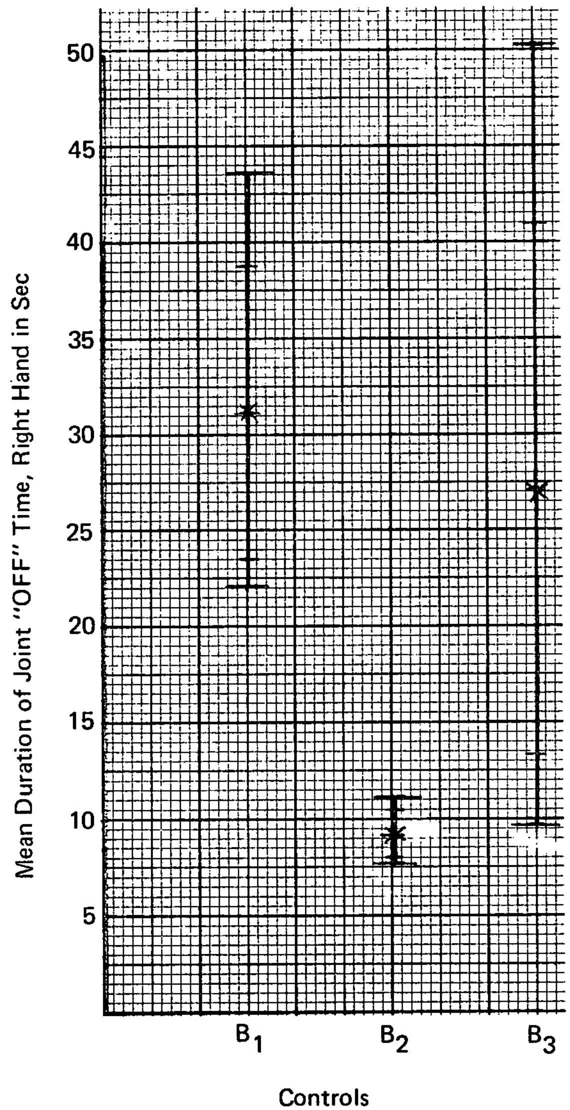
Time Moved: Time Not Moved Ratio, Right Hand
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
B_1
B_2
B_3
Controls

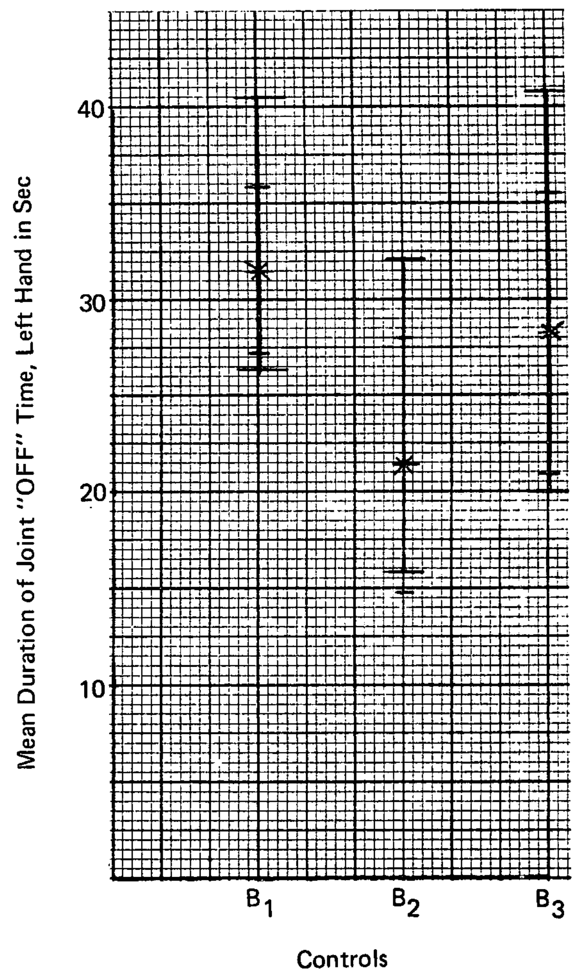

Time Moved and Time Not Moved Ratio, Left Hand
0.30
0.20
0.10
B1
B2
B3
Controls

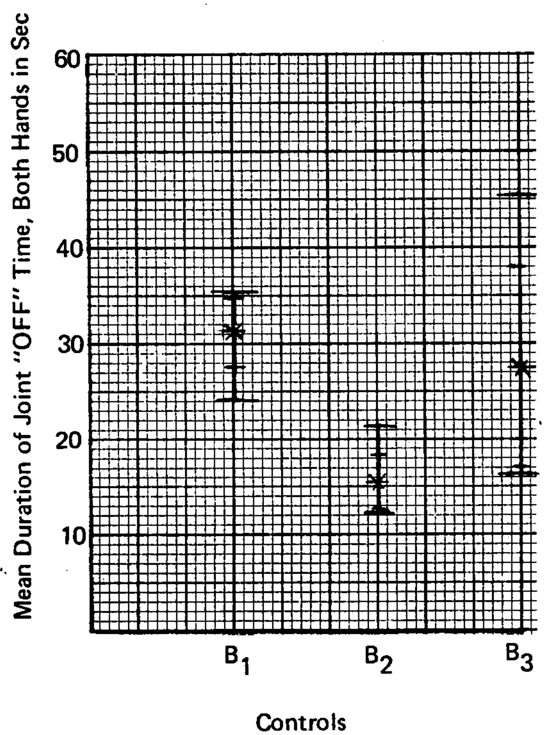

Mean Duration of Joint Movement Time, Right Hand in Sec
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
B1
B2
B3
Controls

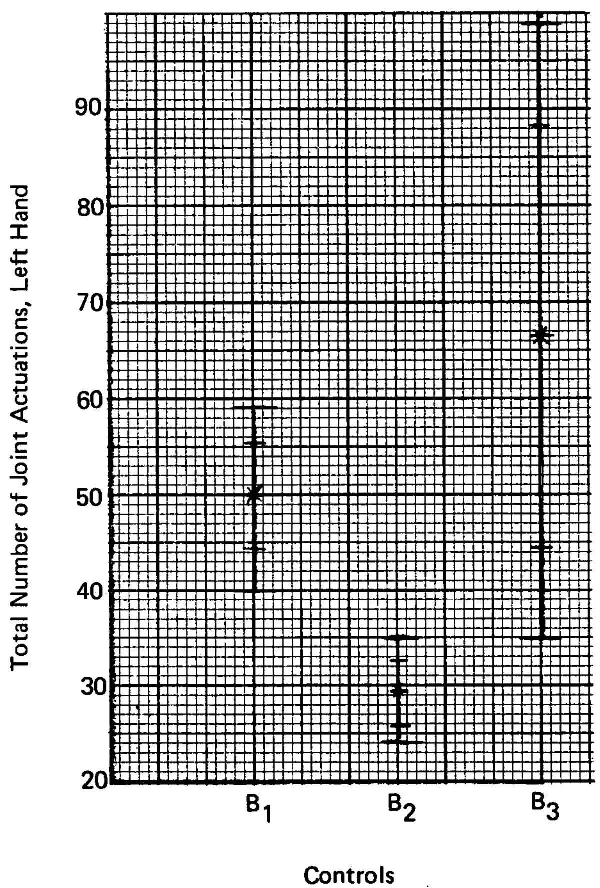

Mean Duration of Joint Movement Time, Left Hand in Sec
7.0
6.0
5.0
4.0
3.0
2.0
1.0
B1
B2
B3
Controls

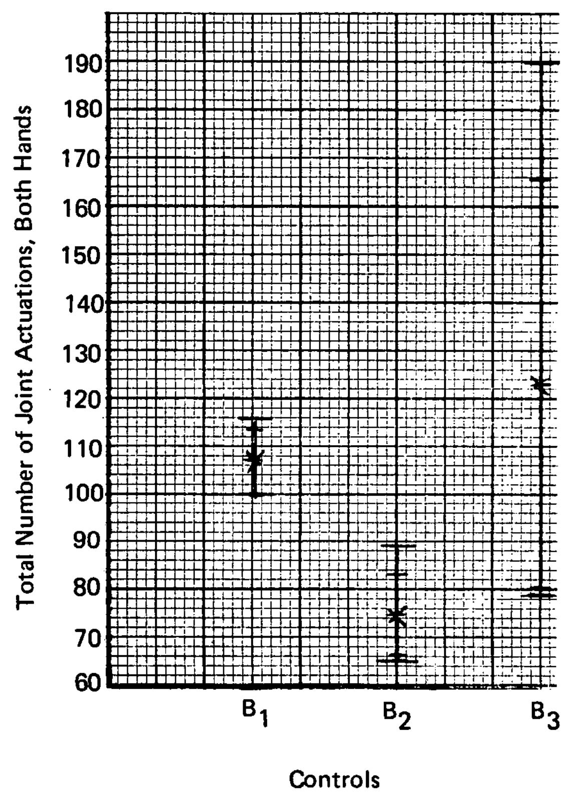

Mean Duration of Joint Movement Time, Both Hands in Sec
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
B_1
B_2
B_3
Controls


Mean Duration of Joint "OFF" Time, Right Hand in Sec
50
45
40
35
30
25
20
15
10
5
B_1
B_2
B_3
Controls

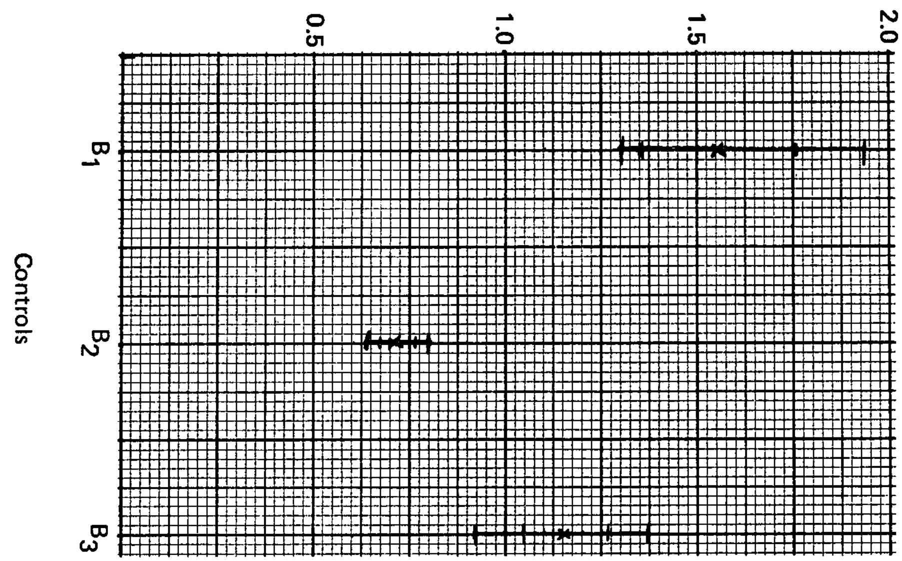

Mean Duration of Joint "OFF" Time, Left Hand in Sec
40
30
20
10
B_1
B_2
B_3
Controls


Mean Duration of Joint "OFF" Time, Both Hands in Sec
60
50
40
30
20
10
B_1
B_2
B_3
Controls

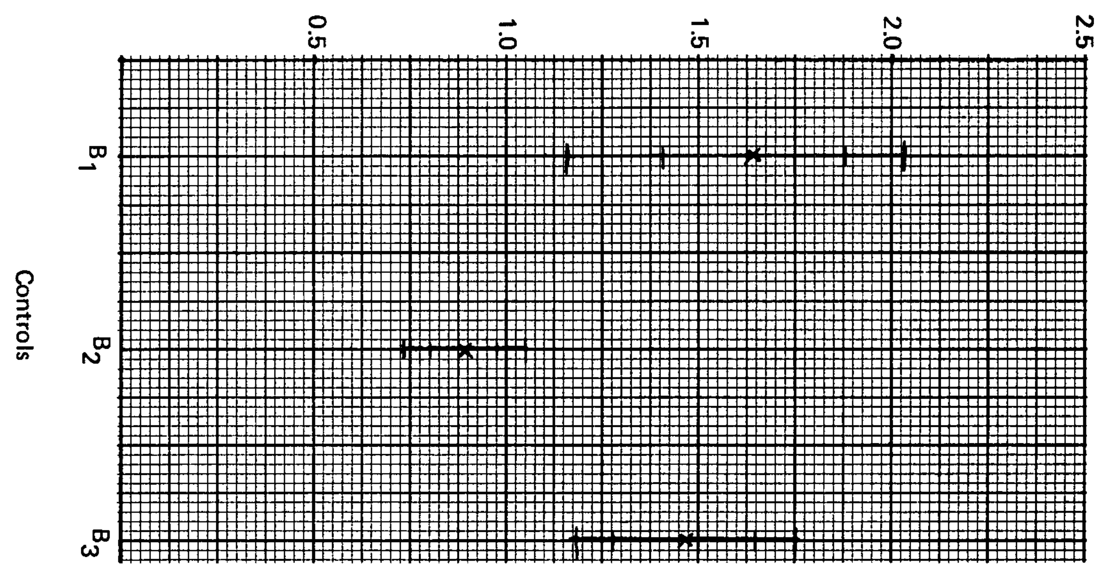

Total Number of Joint Actuations, Left Hand
90
80
70
60
50
40
30
20
B_1
B_2
B_3
Controls


Total Number of Joint Actuations, Both Hands
190
180
170
160
150
140
130
120
110
100
90
80
70
60
B_1
B_2
B_3
Controls

Total Time to Complete Removal (Subtask 1) Min

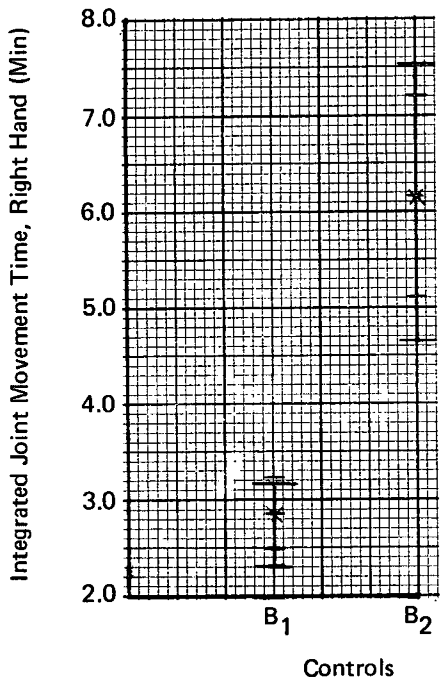


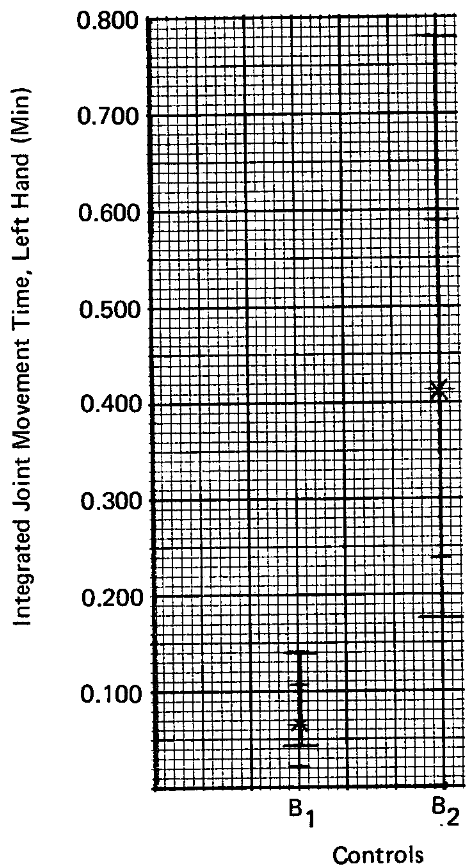
Total Time to Complete Replacement (Subtask 2) Min

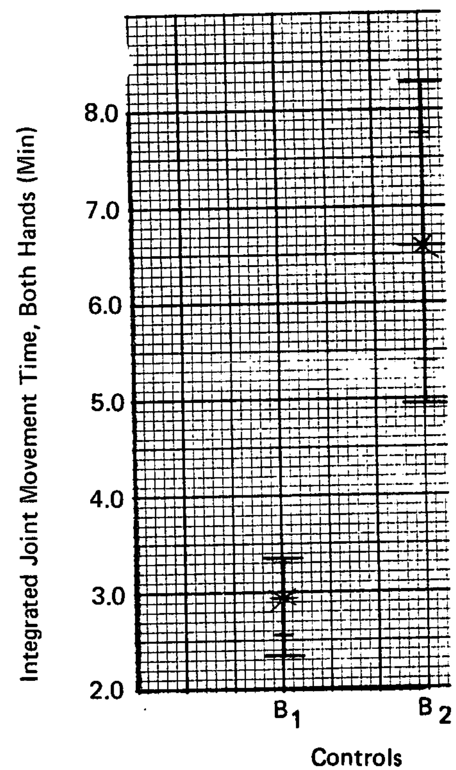


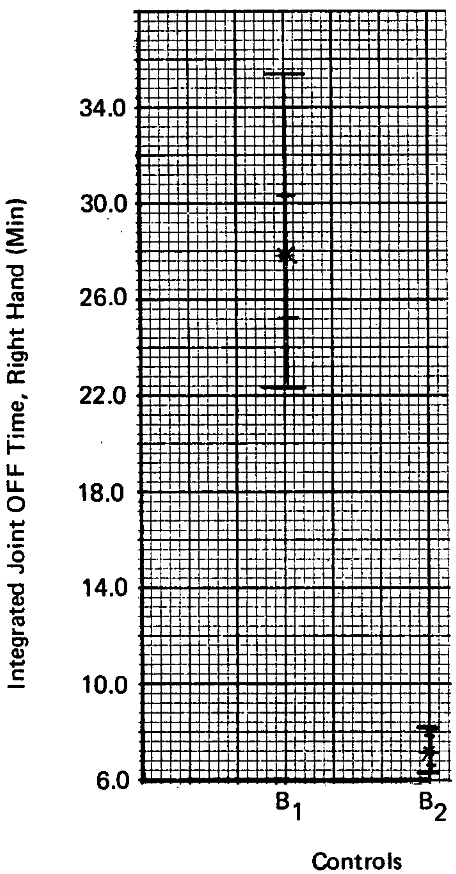
MANIPULATION EXPERIMENT E2: BATTERY REPLACEMENT

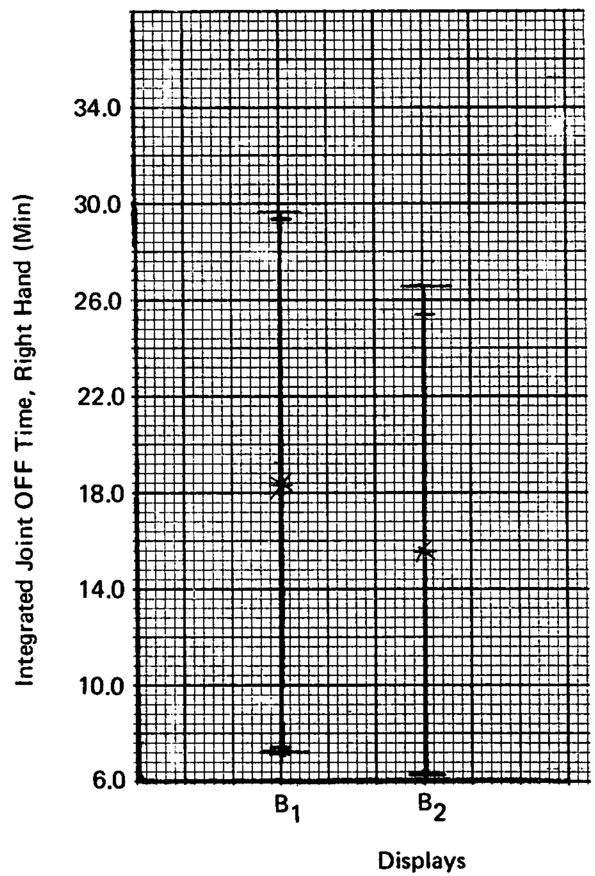
GRAPHICAL PRESENTATION OF SIGNIFICANT RESULTS

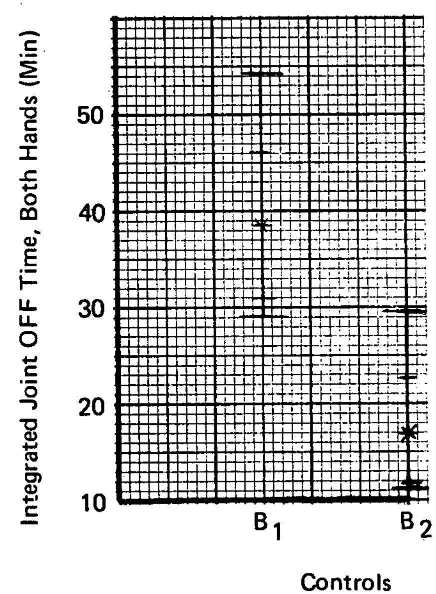

Integrated Joint Movement Time, Right Hand (Min)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
B_1
B_2
Controls

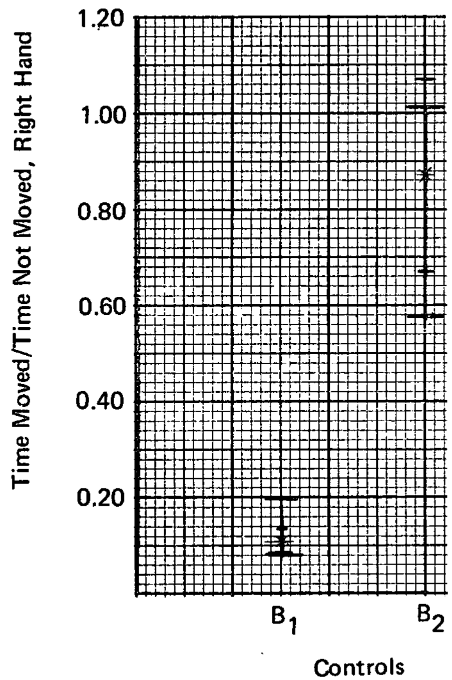

Integrated Joint Movement Time, Left Hand (Min)
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
B_1
B_2
Controls

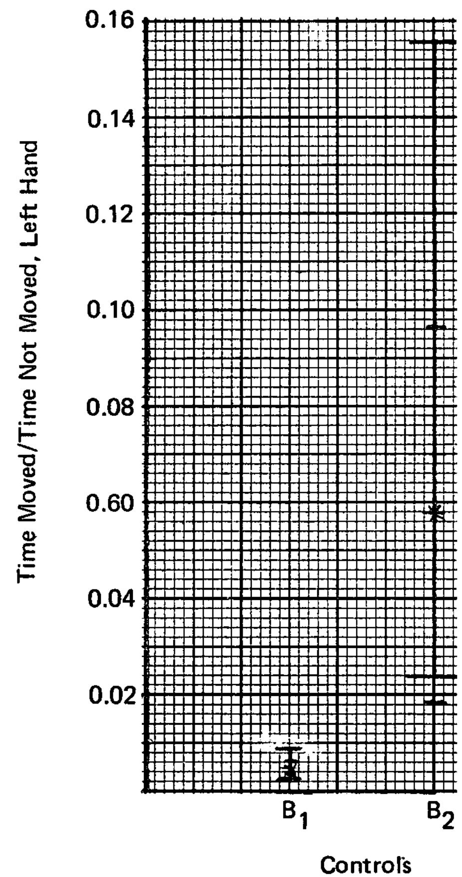

Integrated Joint Movement Time, Both Hands (Min)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
B_1
B_2
Controls

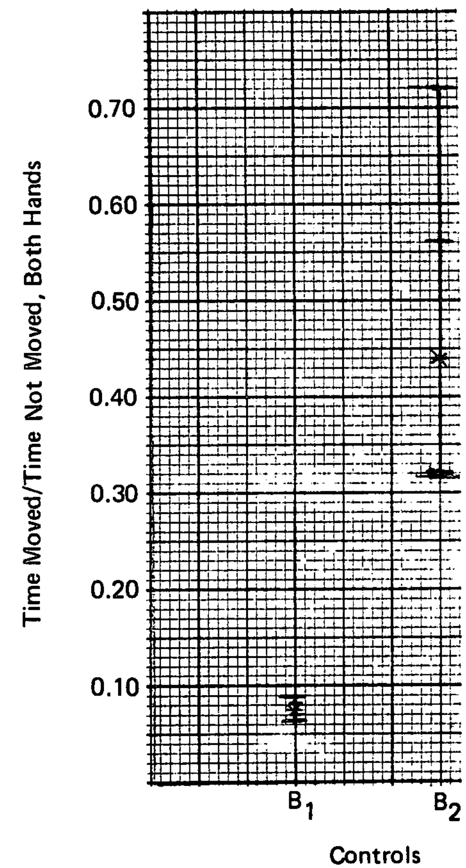

Integrated Joint OFF Time, Right Hand (Min)
34.0
30.0
26.0
22.0
18.0
14.0
10.0
6.0
B_1
B_2
Controls

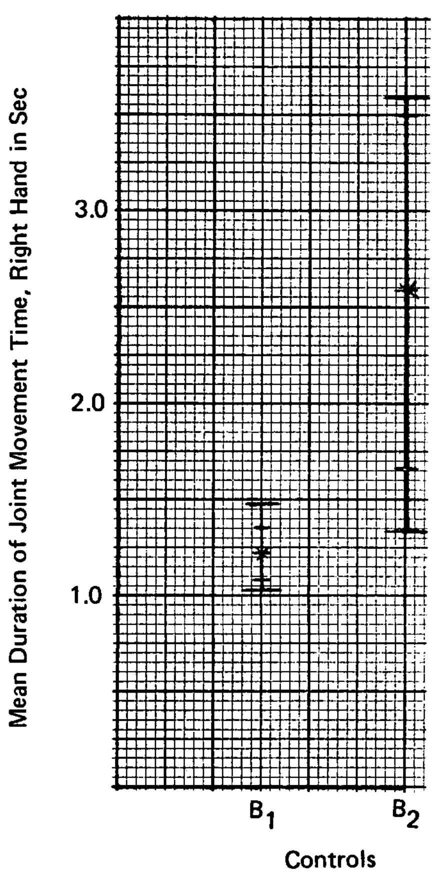

Integrated Joint OFF Time, Right Hand (Min)
34.0
30.0
26.0
22.0
18.0
14.0
10.0
6.0
B_1
B_2
Displays


Integrated Joint OFF Time, Both Hands (Min)
50
40
30
20
10
B_1
B_2
Controls

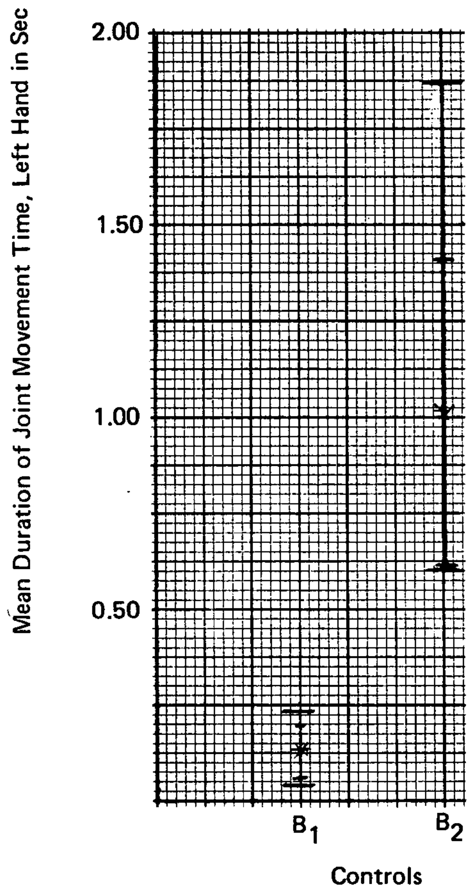

Time Moved/Time Not Moved, Right Hand
1.20
1.00
0.80
0.60
0.40
0.20
B_1
B_2
Controls


Time Moved/Time Not Moved, Left Hand
0.16
0.14
0.12
0.10
0.08
0.60
0.04
0.02
B_1
B_2
Controls

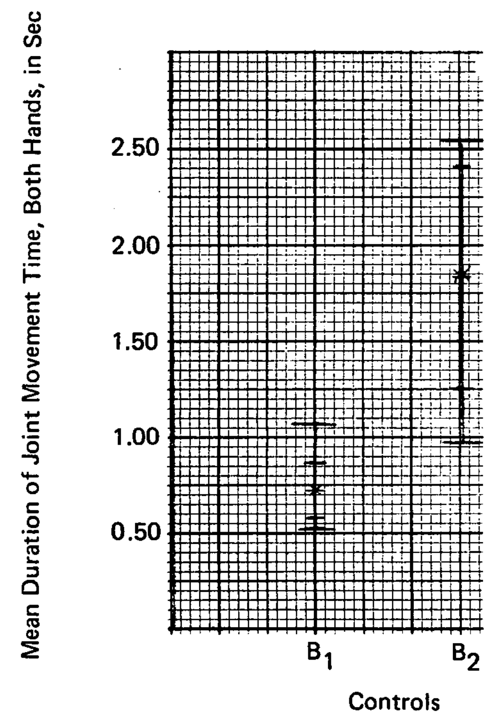

Time Moved/Time Not Moved, Both Hands
0.70
0.60
0.50
0.40
0.30
0.20
0.10
B_1
B_2
Controls



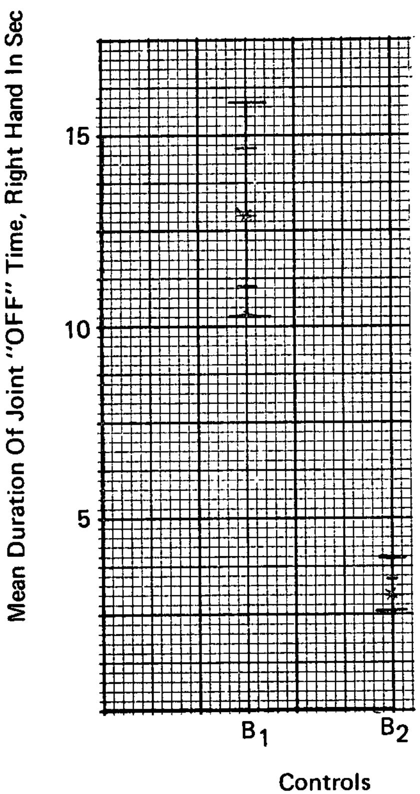
Mean Duration of Joint Movement Time, Right Hand in Sec
3.0
2.0
1.0
B1
B2
Controls

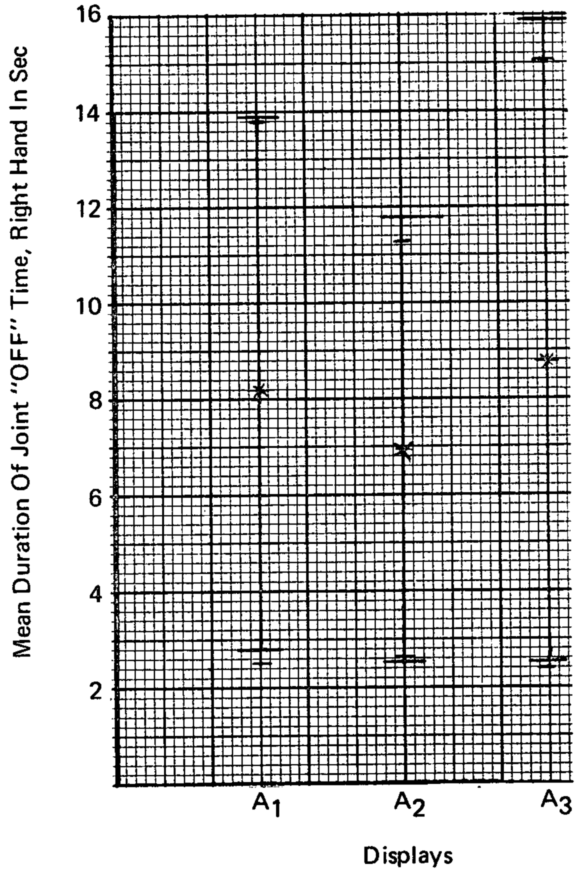


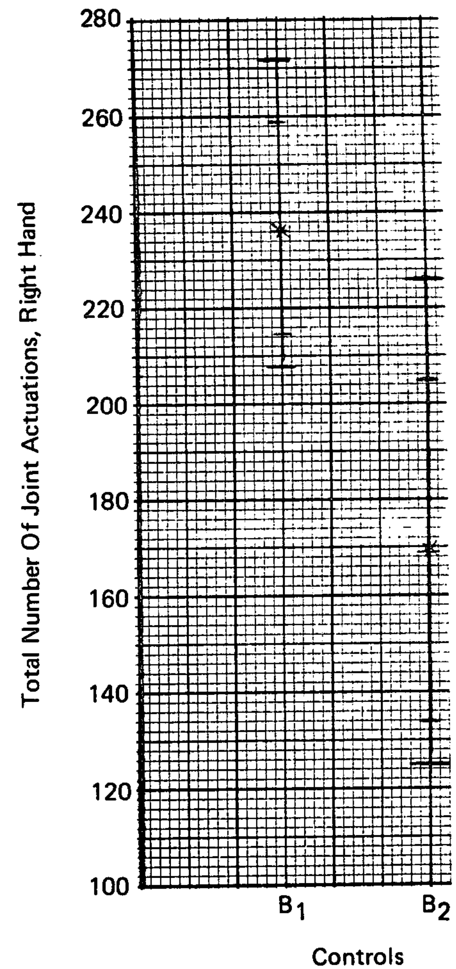
Mean Duration of Joint Movement Time, Left Hand in Sec
2.00
1.50
1.00
0.50
B1
B2
Controls

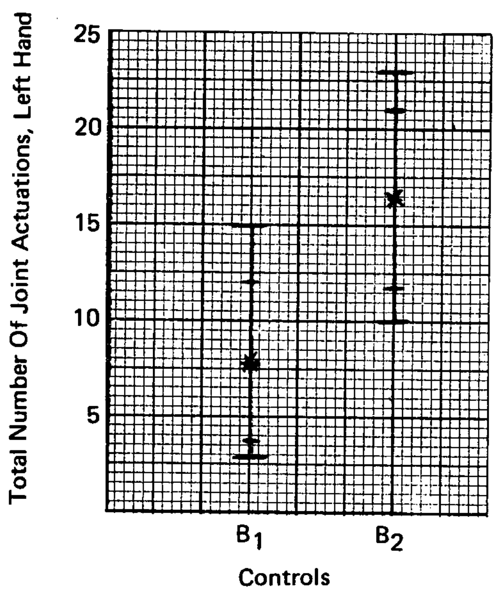


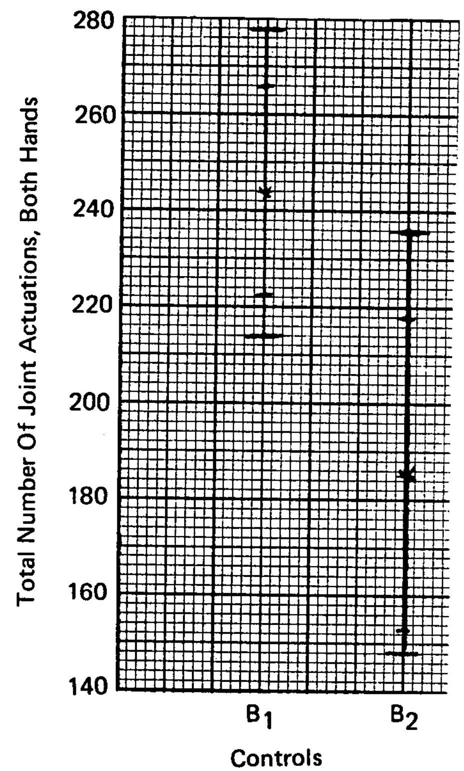
Mean Duration of Joint Movement Time, Both Hands, in Sec
2.50
2.00
1.50
1.00
0.50
B1
B2
Controls

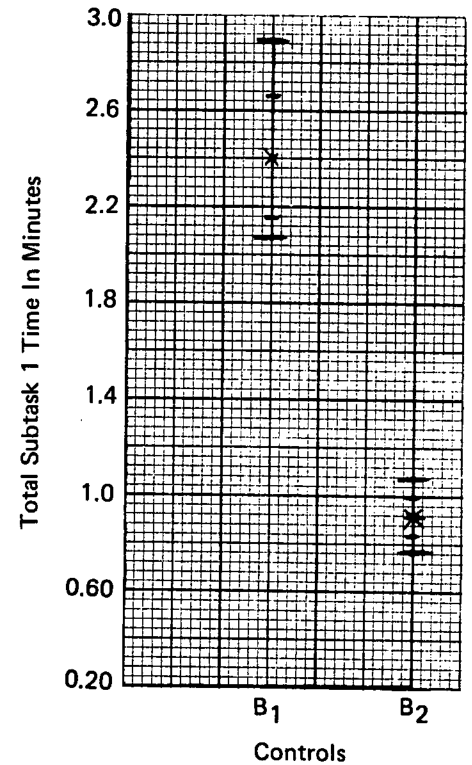

Mean Duration Of Joint "OFF" Time, Right Hand In Sec
15
10
5
B1
B2
Controls

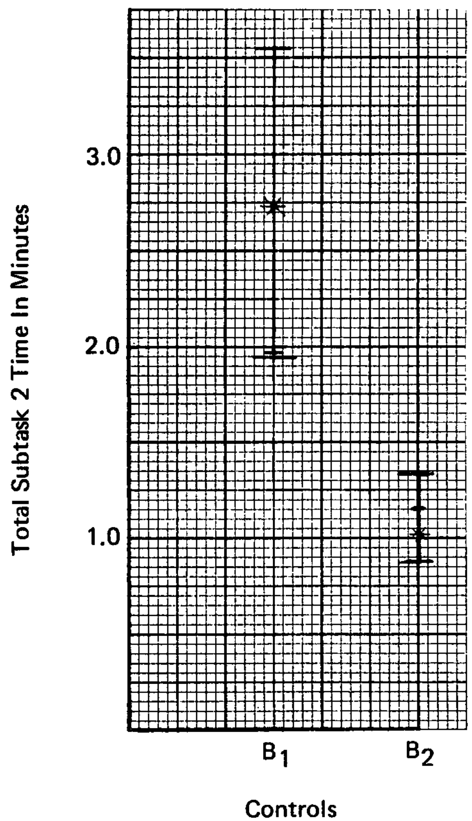

Mean Duration Of Joint "OFF" Time, Right Hand In Sec
16
14
12
10
8
6
4
2
A1
A2
A3
Displays

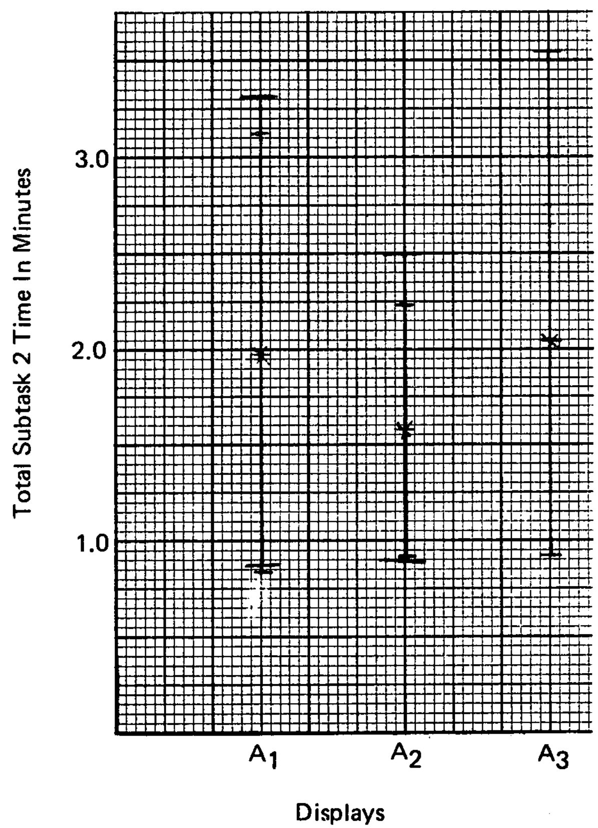

Total Number Of Joint Actuations, Right Hand
280
260
240
220
200
180
160
140
120
100
B1
B2
Controls

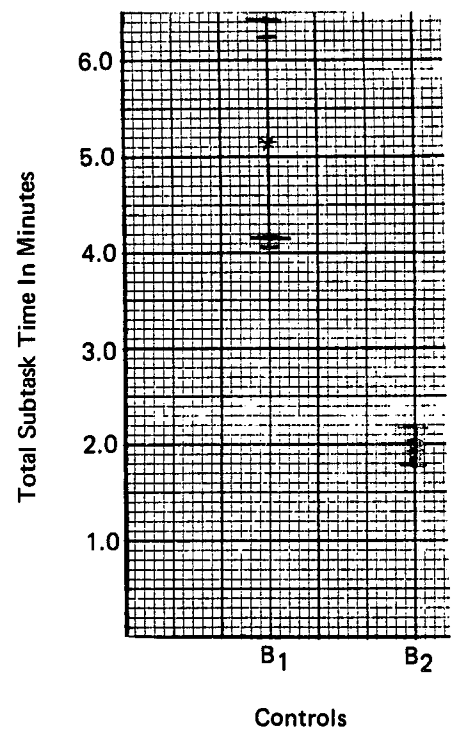

Total Number Of Joint Actuations, Left Hand
25
20
15
10
5
B1
B2
Controls

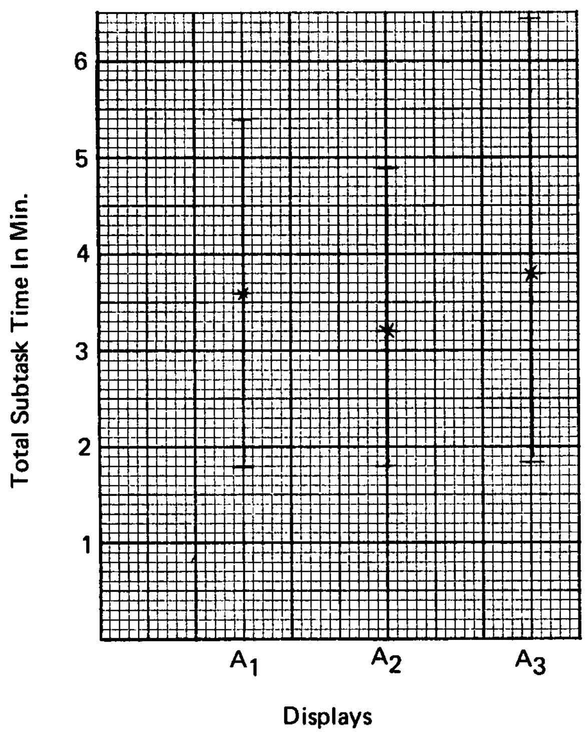

Total Number Of Joint Actuations, Both Hands
280
260
240
220
200
180
160
140
B1
B2
Controls

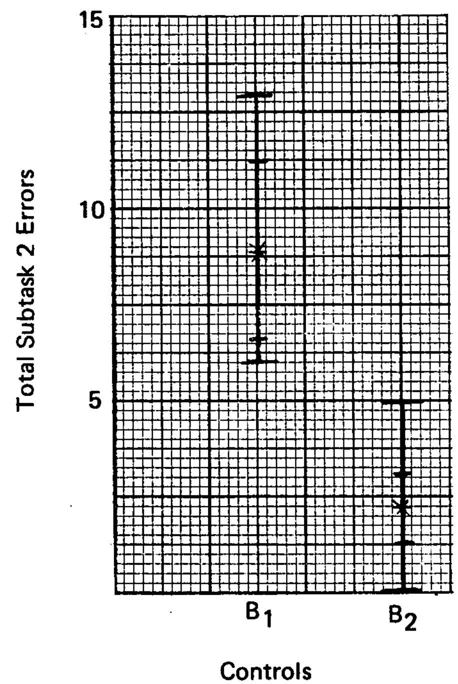

Total Subtask 1 Time In Minutes
3.0
2.6
2.2
1.8
1.4
1.0
0.60
0.20
B1
B2
Controls

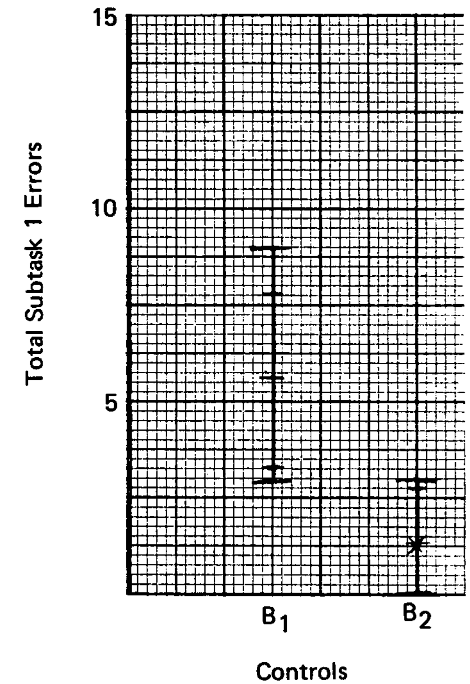

Total Subtask 2 Time In Minutes
3.0
2.0
1.0
B_1
B_2
Controls

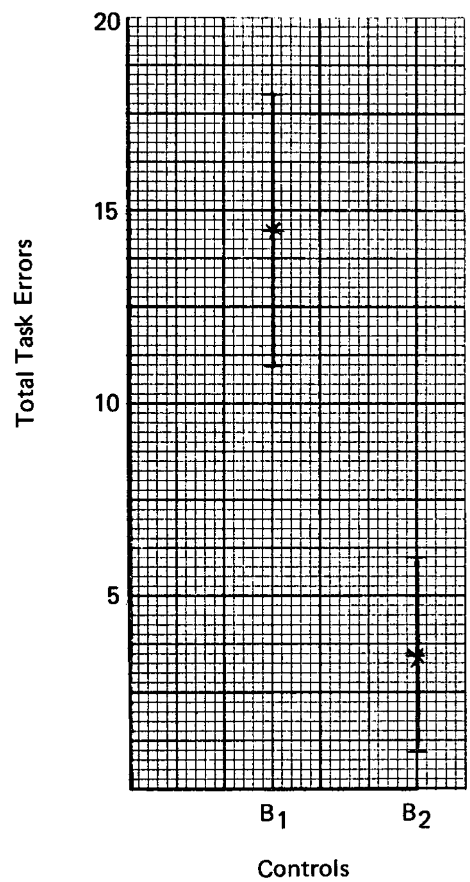

Total Subtask 2 Time In Minutes
3.0
2.0
1.0
A_1
A_2
A_3
Displays


Total Subtask Time In Minutes
6.0
5.0
4.0
3.0
2.0
1.0
B_1
B_2
Controls


Total Subtask Time In Min.
1
2
3
4
5
6
A1
A2
A3
Displays

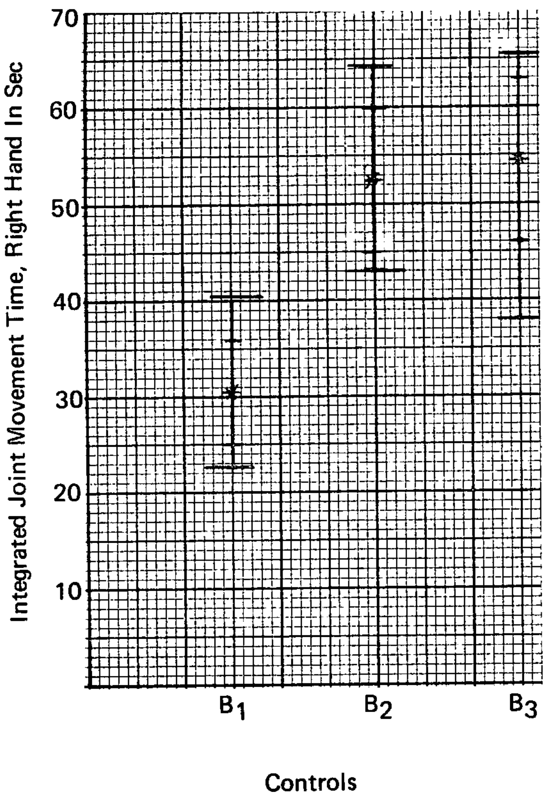

Total Subtask 2 Errors
5
10
15
B1
B2
Controls

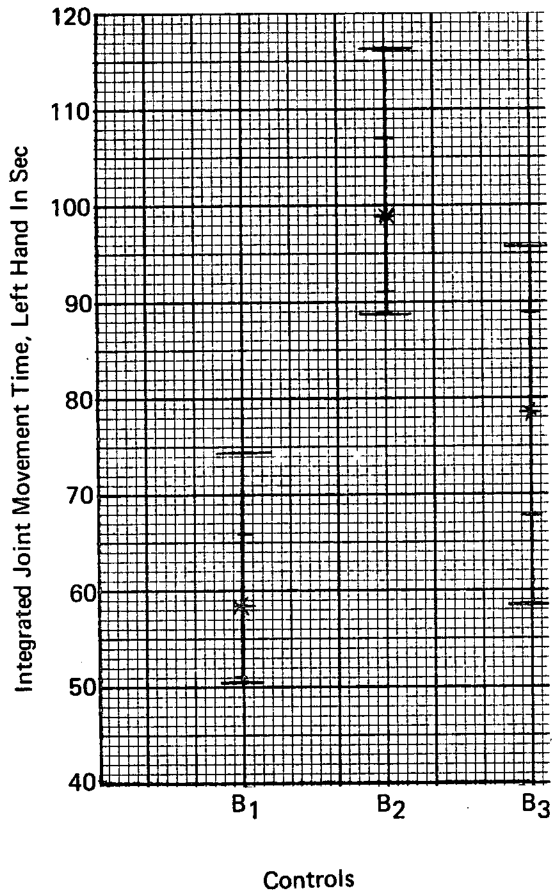

Total Subtask 1 Errors
5
10
15
B1
B2
Controls

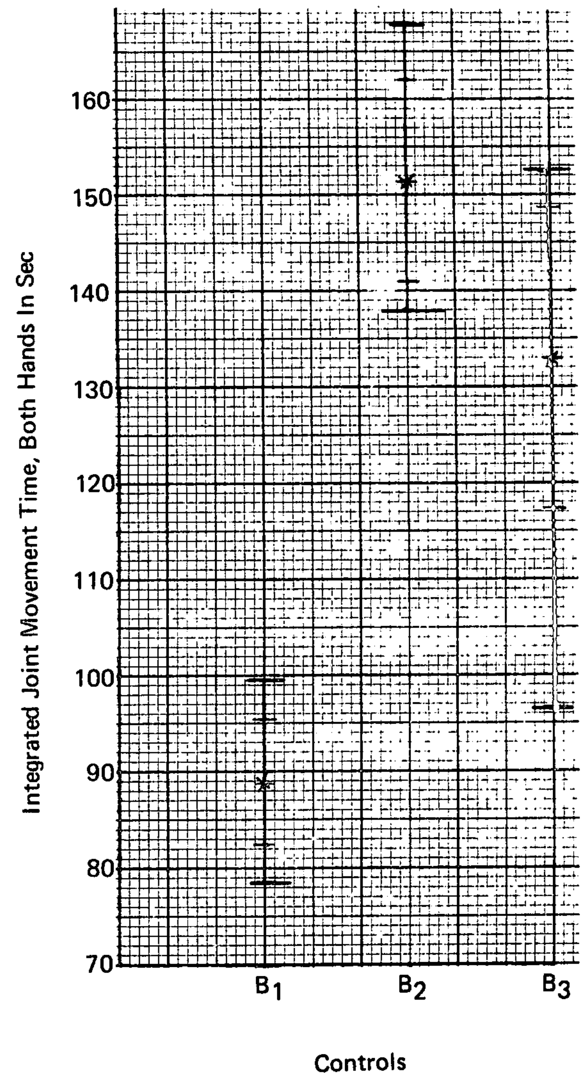

Total Task Errors
20
15
10
5
B_1
B_2
Controls

MANIPULATION EXPERIMENT E3: COMPARTMENT INSPECTION

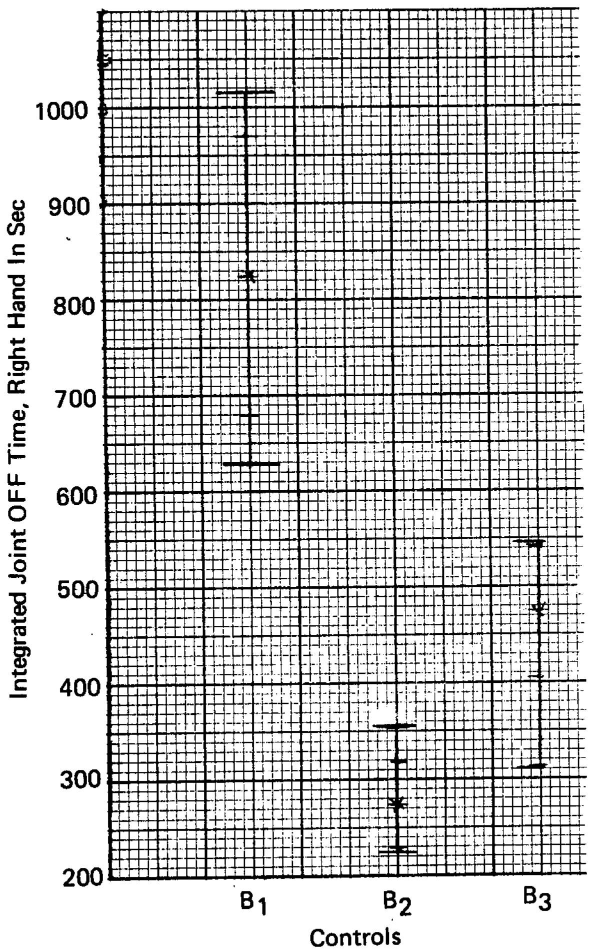
GRAPHICAL PRESENTATION OF
SIGNIFICANT RESULTS

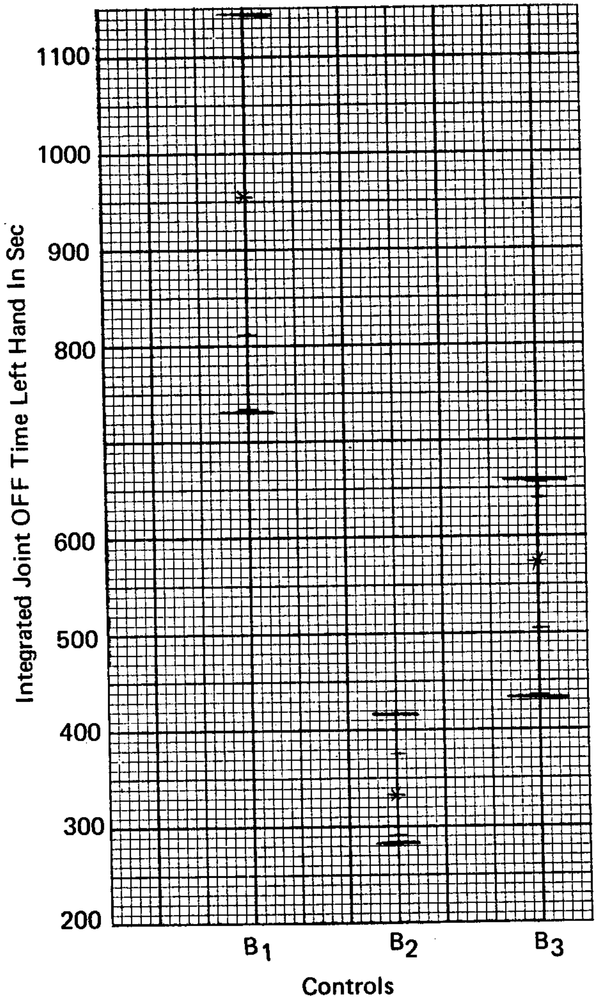

Integrated Joint Movement Time, Right Hand In Sec
70
60
50
40
30
20
10
B1
B2
B3
Controls

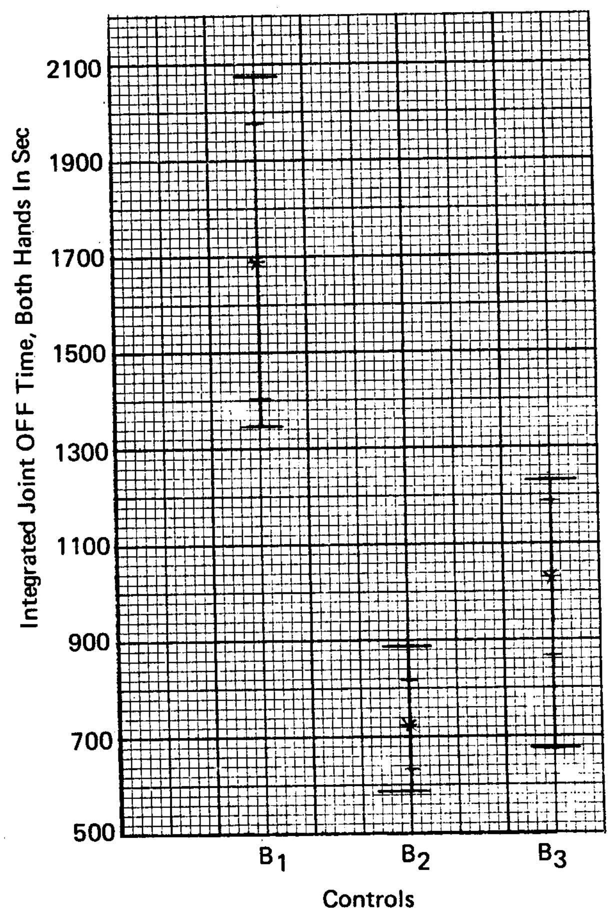

Integrated Joint Movement Time, Left Hand In Sec
120
110
100
90
80
70
60
50
40
B1
B2
B3
Controls

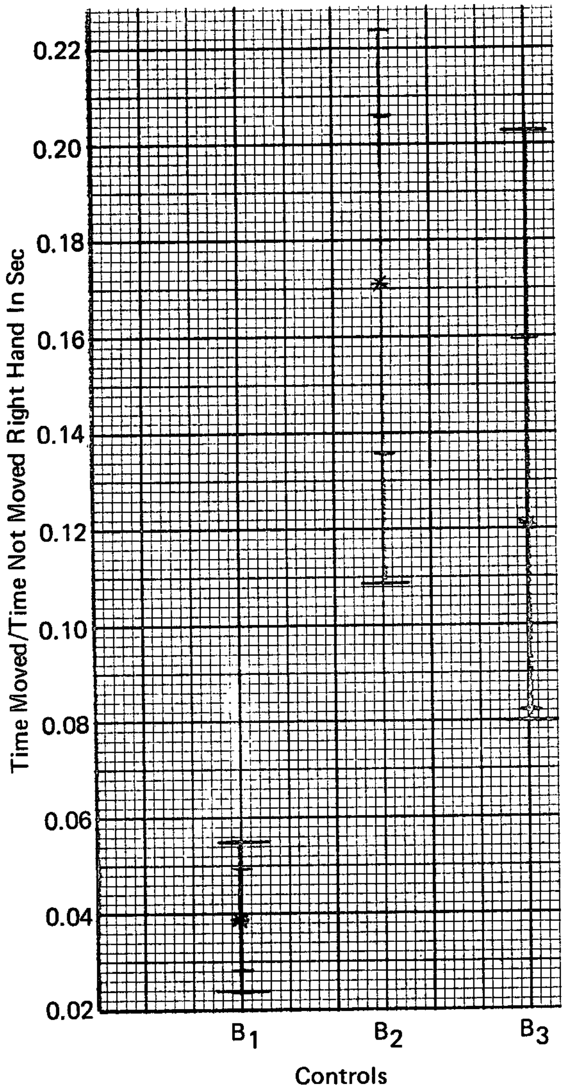

Integrated Joint Movement Time, Both Hands In Sec
160
150
140
130
120
110
100
90
80
70
B1
B2
B3
Controls

C.4

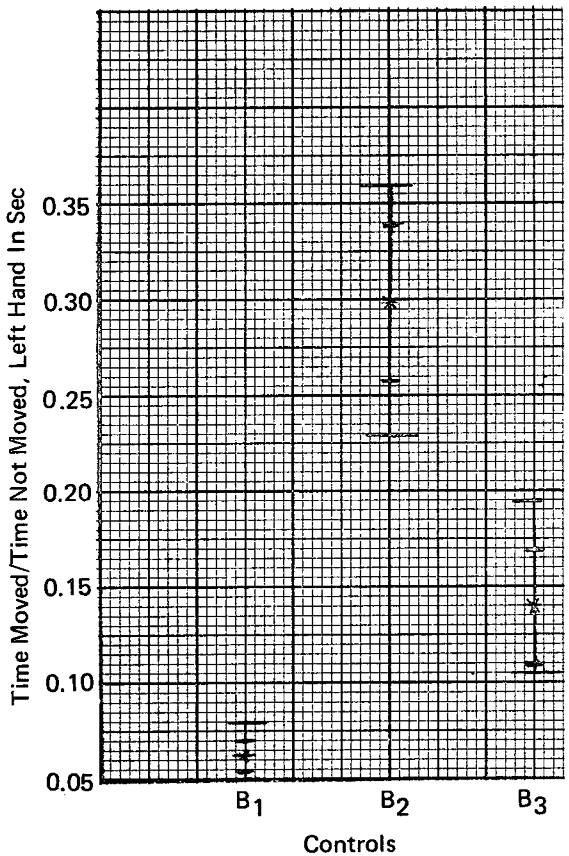

Integrated Joint OFF Time, Right Hand In Sec
1000
900
800
700
600
500
400
300
200
B1
B2
B3
Controls


Integrated Joint OFF Time Left Hand In Sec
1100
1000
900
800
600
500
400
300
200
B1
B2
B3
Controls

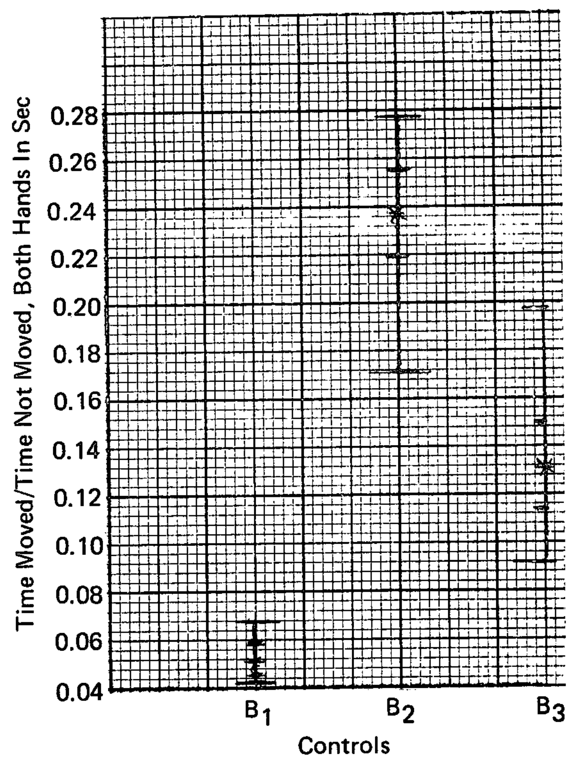

Integrated Joint OFF Time, Both Hands In Sec
2100
1900
1700
1500
1300
1100
900
700
500
B1
B2
B3
Controls



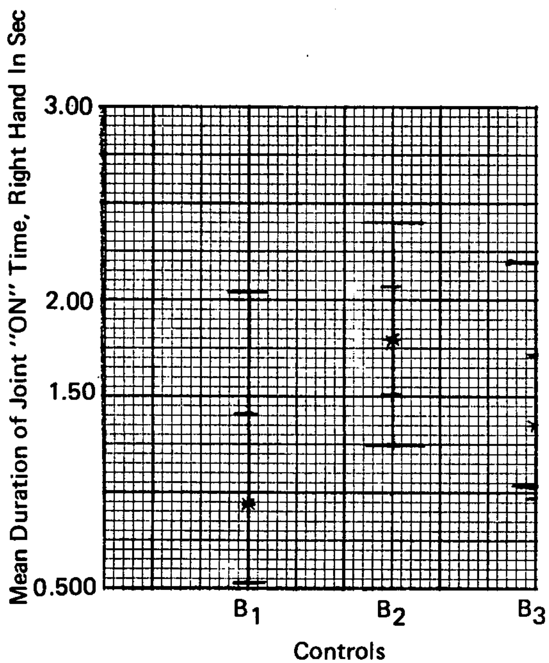
Time Moved/Time Not Moved Right Hand In Sec
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
B_1
B_2
B_3
Controls

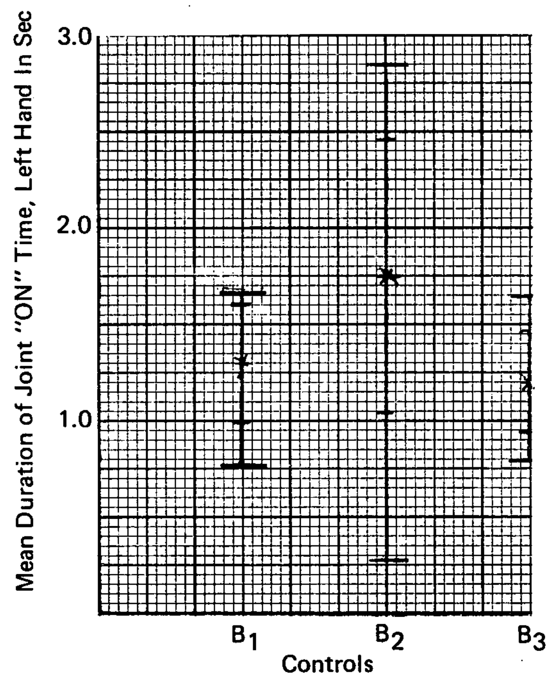


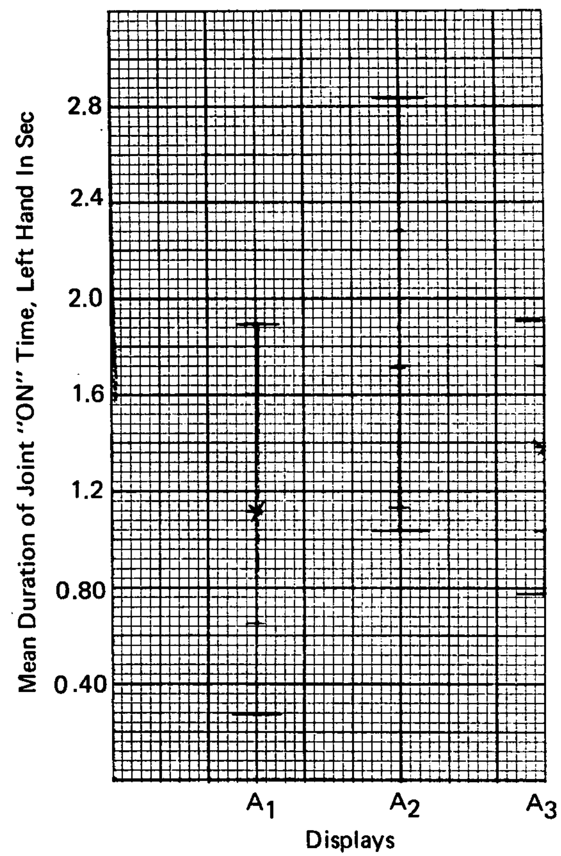
Time Moved/Time Not Moved, Left Hand In Sec
0.35
0.30
0.25
0.20
0.15
0.10
0.05
B_1
B_2
B_3
Controls

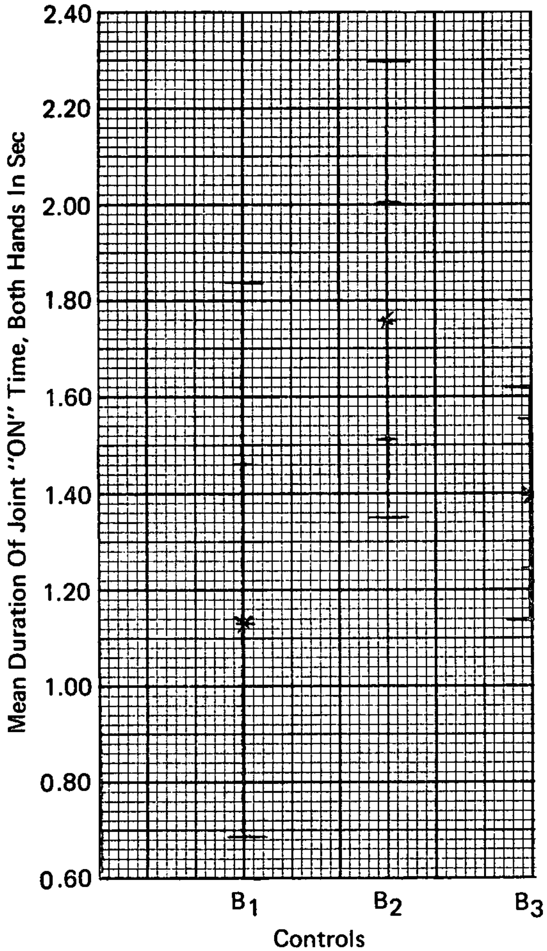


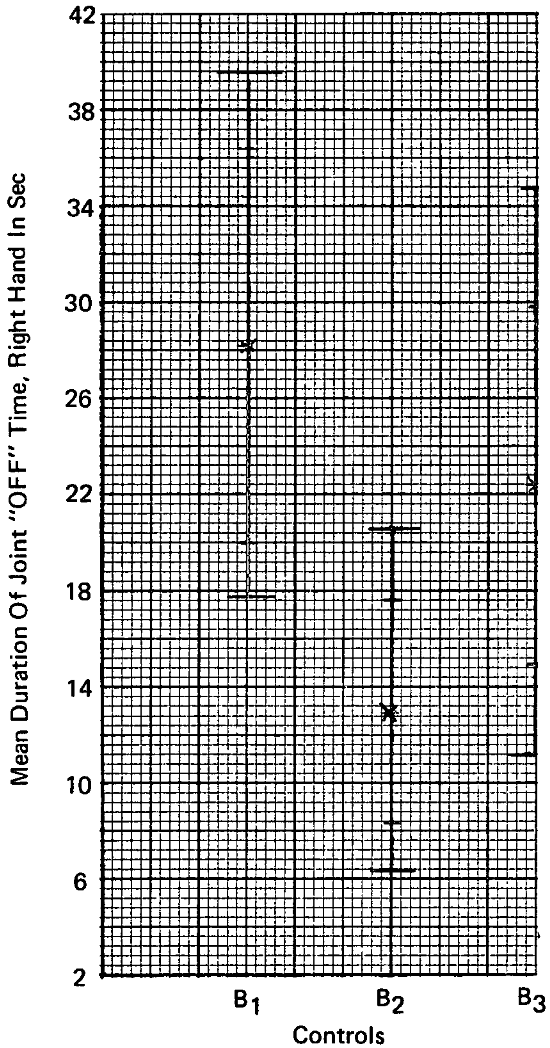
Time Moved/Time Not Moved, Both Hands In Sec
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
B_1
B_2
B_3
Controls

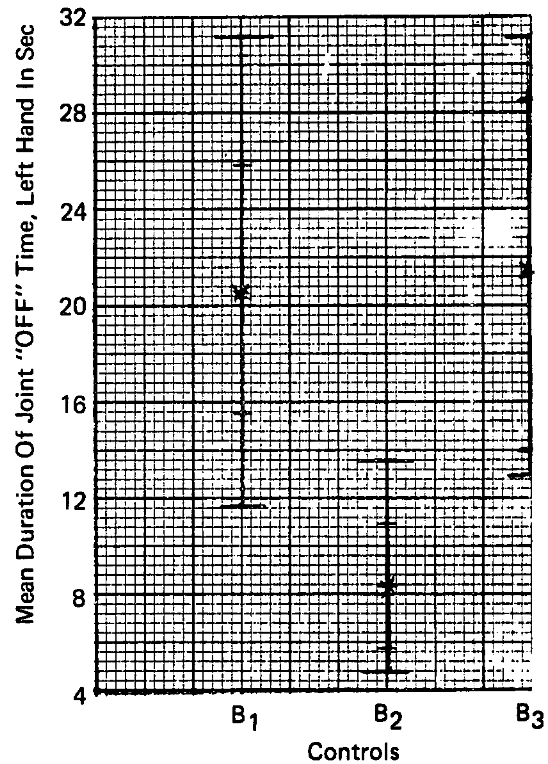

Mean Duration of Joint "ON" Time, Right Hand In Sec
3.00
2.00
1.50
0.500
B1
B2
B3
Controls

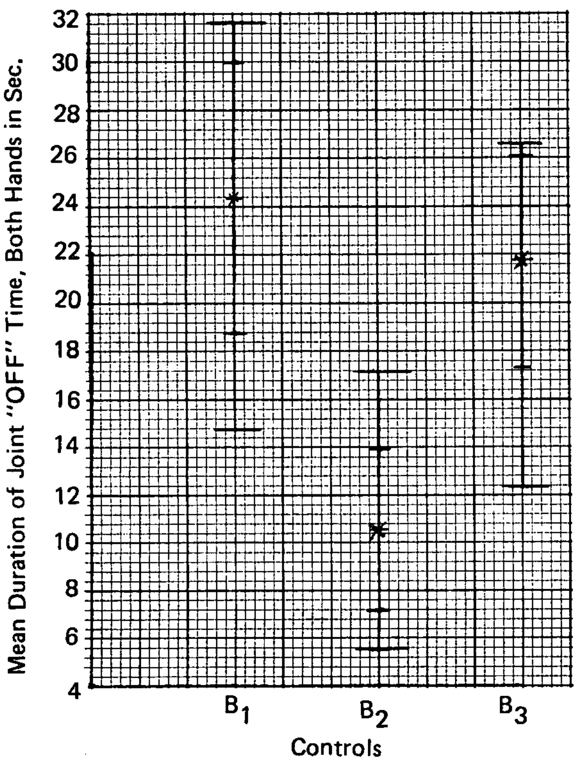

Mean Duration of Joint "ON" Time, Left Hand In Sec
3.0
2.0
1.0
B1
B2
B3
Controls

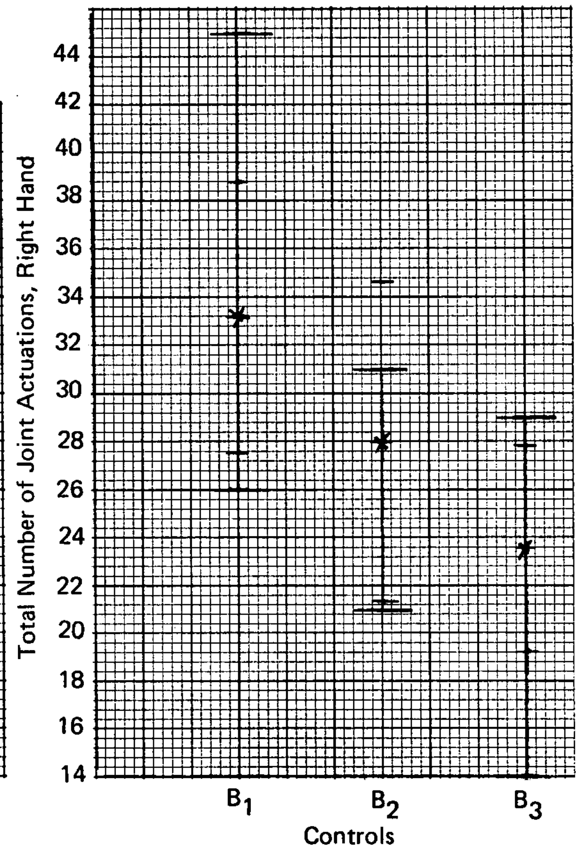

Mean Duration of Joint "ON" Time, Left Hand In Sec
2.8
2.4
2.0
1.6
1.2
0.80
0.40
A1
A2
A3
Displays

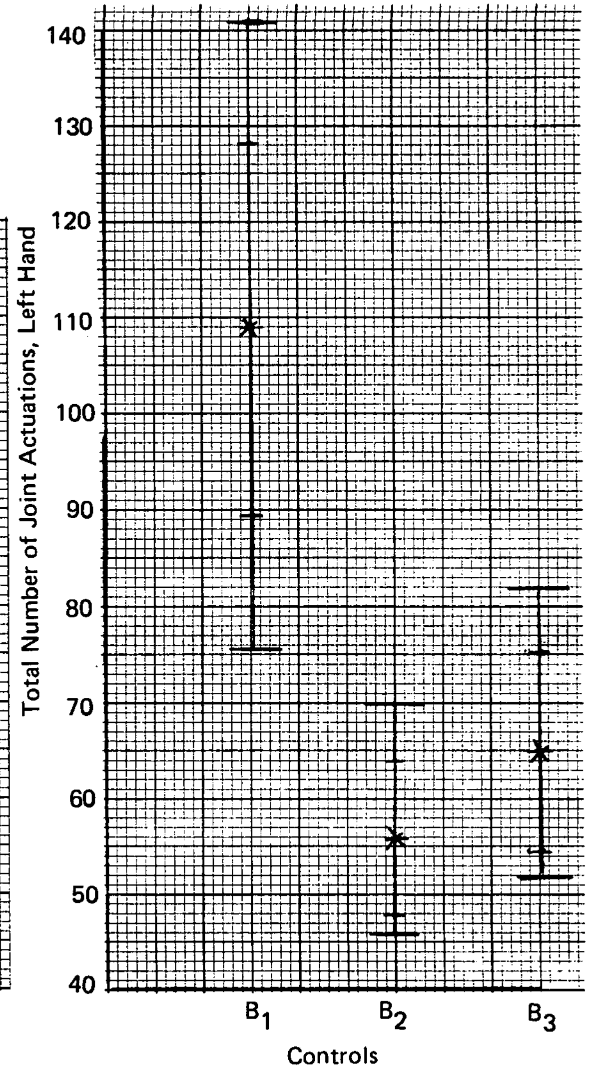

Mean Duration Of Joint "ON" Time, Both Hands In Sec
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
B1
B2
B3
Controls

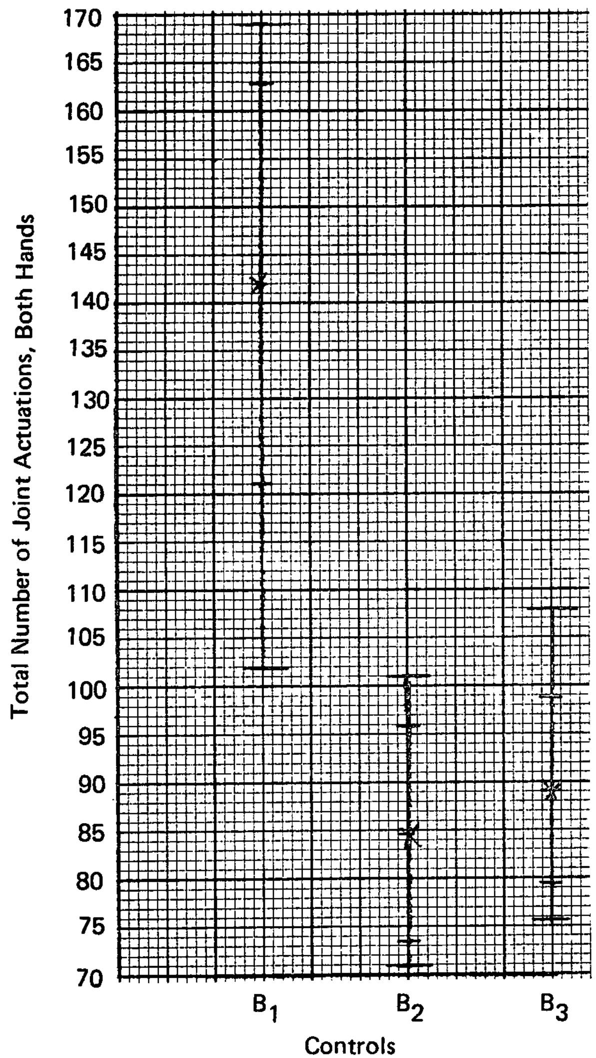

Mean Duration Of Joint "OFF" Time, Right Hand In Sec
42
38
34
30
26
22
18
14
10
6
2
B1
B2
B3
Controls

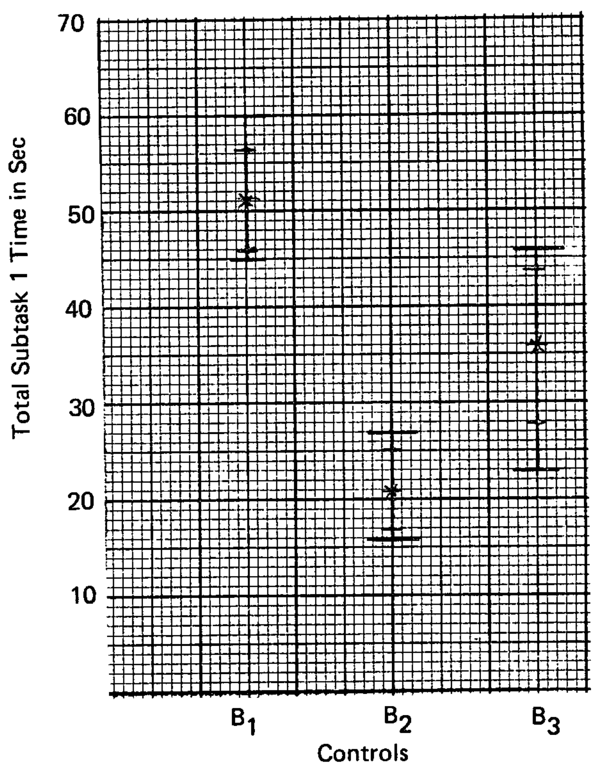

Mean Duration Of Joint "OFF" Time, Left Hand In Sec
32
28
24
20
16
12
8
4
B1
B2
B3
Controls

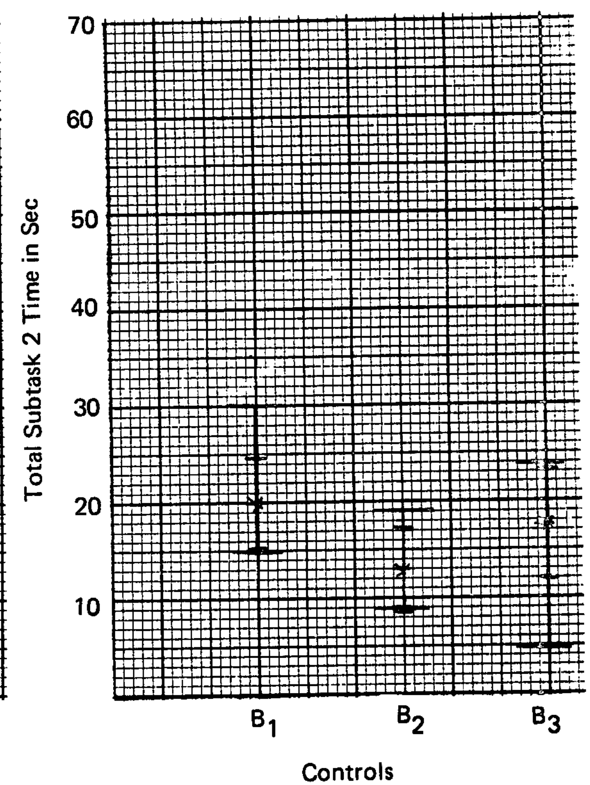

Mean Duration of Joint "OFF" Time, Both Hands in Sec.
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
B_1
B_2
B_3
Controls

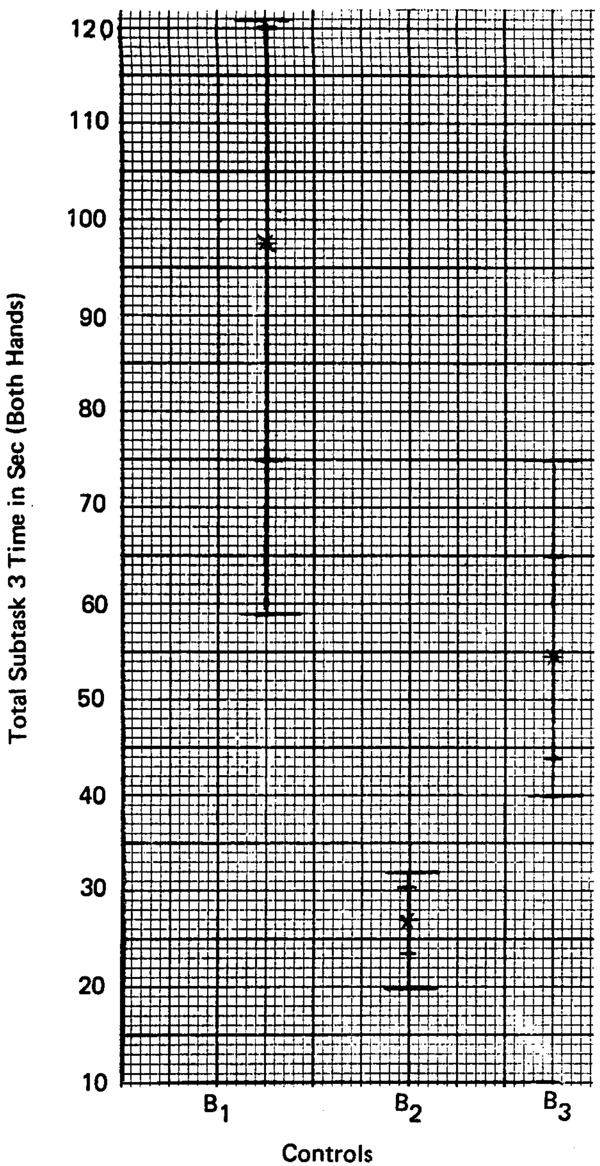

Total Number of Joint Actuations, Right Hand
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
B_1
B_2
B_3
Controls

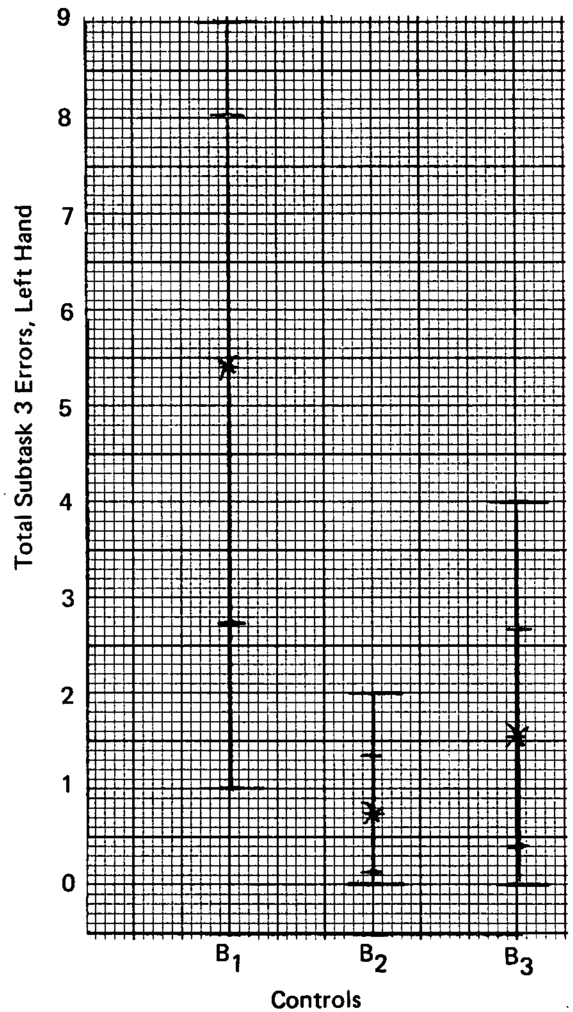

Total Number of Joint Actuations, Left Hand
40
50
60
70
80
90
100
110
120
130
140
B_1
B_2
B_3
Controls

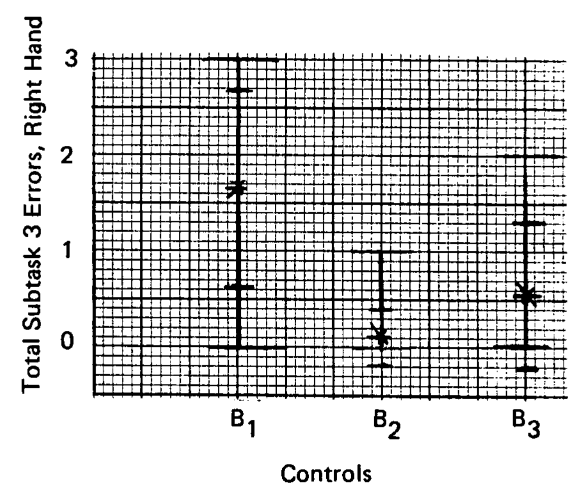

Total Number of Joint Actuations, Both Hands
170
165
160
155
150
145
140
135
130
125
120
115
110
105
100
95
90
85
80
75
70
B1
B2
B3
Controls


Total Subtask 1 Time in Sec
70
60
50
40
30
20
10
B1
B2
B3
Controls


Total Subtask 2 Time in Sec
70
60
50
40
30
20
10
B1
B2
B3
Controls

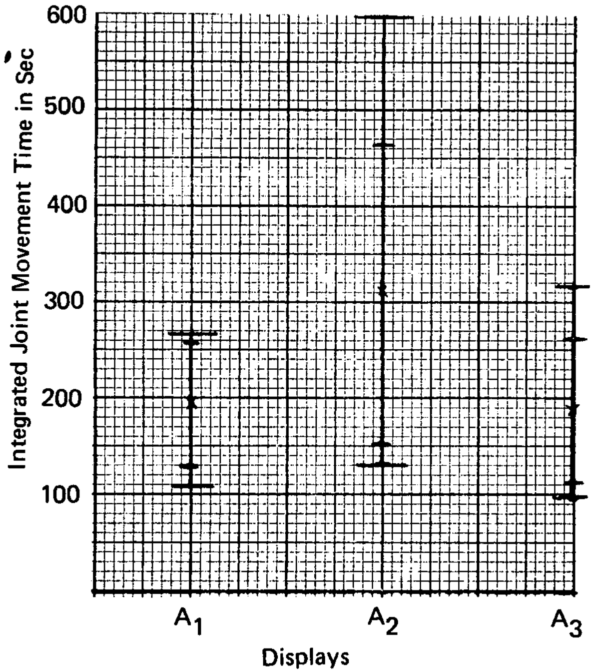

Total Subtask 3 Time in Sec (Both Hands)
120
110
100
90
80
70
60
50
40
30
20
10
B_1
B_2
B_3
Controls

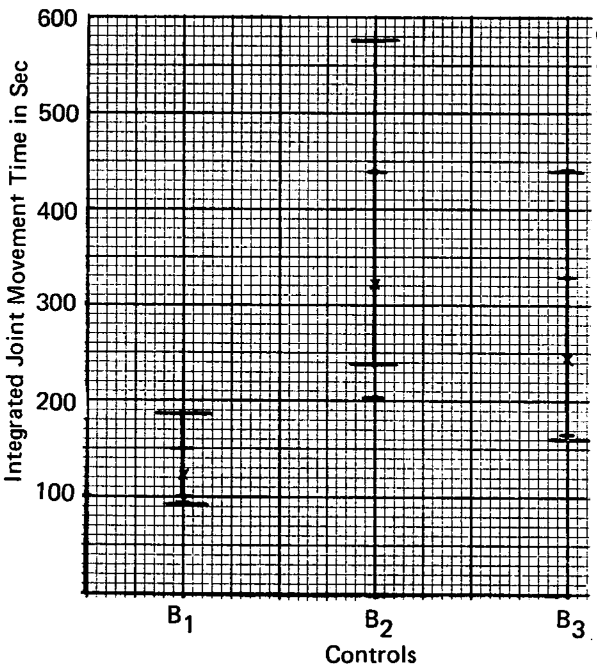

Total Subtask 3 Errors, Left Hand
9
8
7
6
5
4
3
2
1
0
B_1
B_2
B_3
Controls

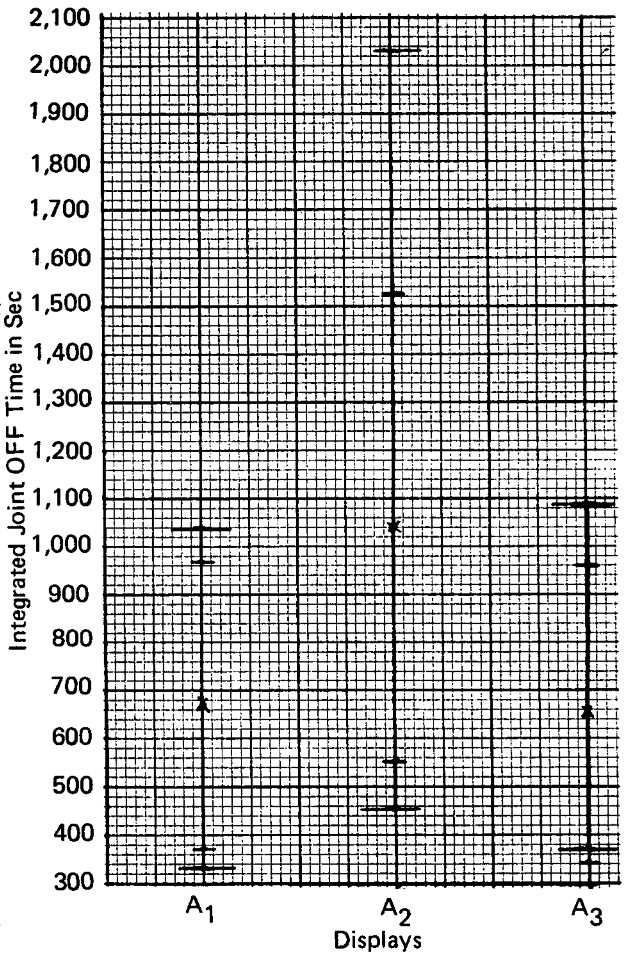

Total Subtask 3 Errors, Right Hand
3
2
1
0
B_1
B_2
B_3
Controls

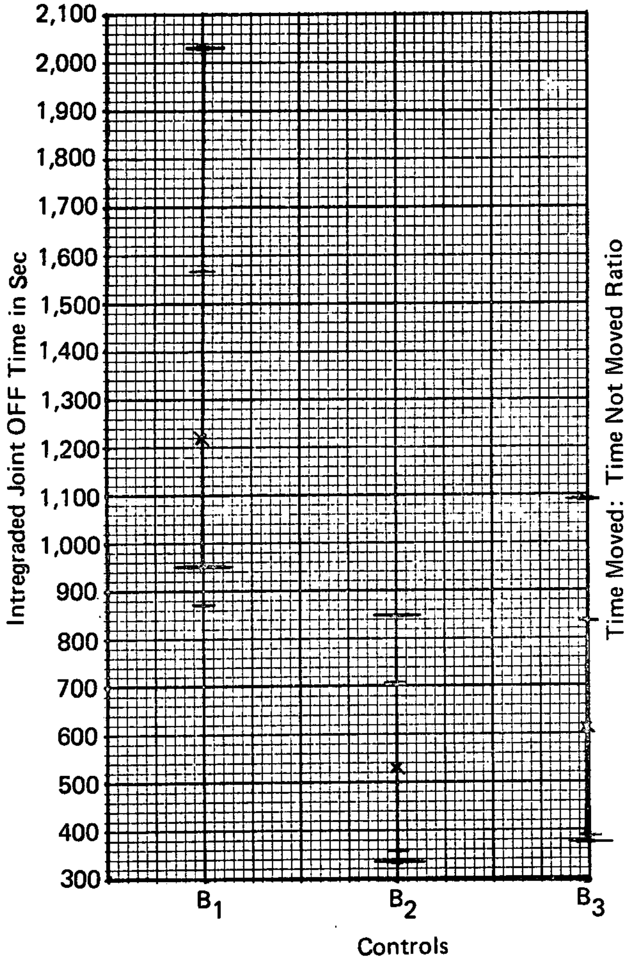
MANIPULATION EXPERIMENT E4: ANTENNA INSTALLATION

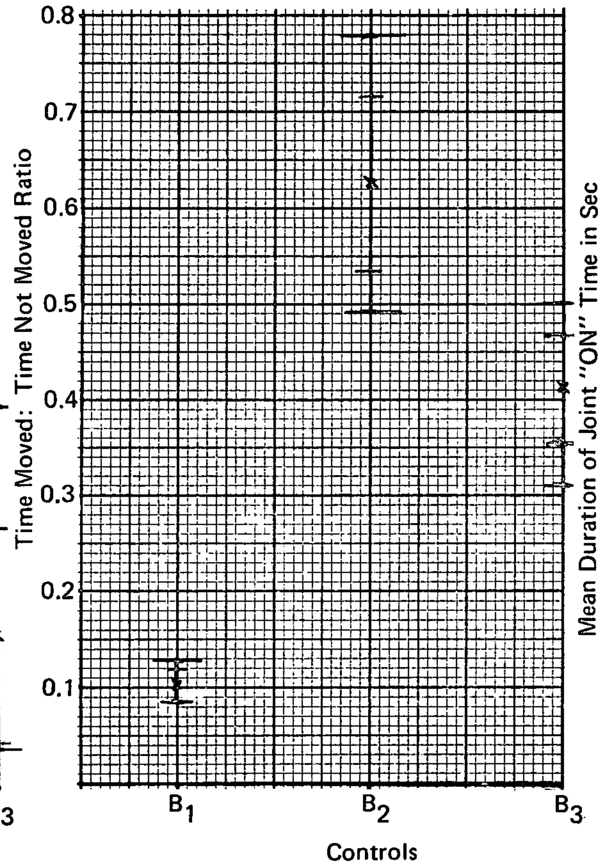
GRAPHICAL PRESENTATION OF SIGNIFICANT RESULTS

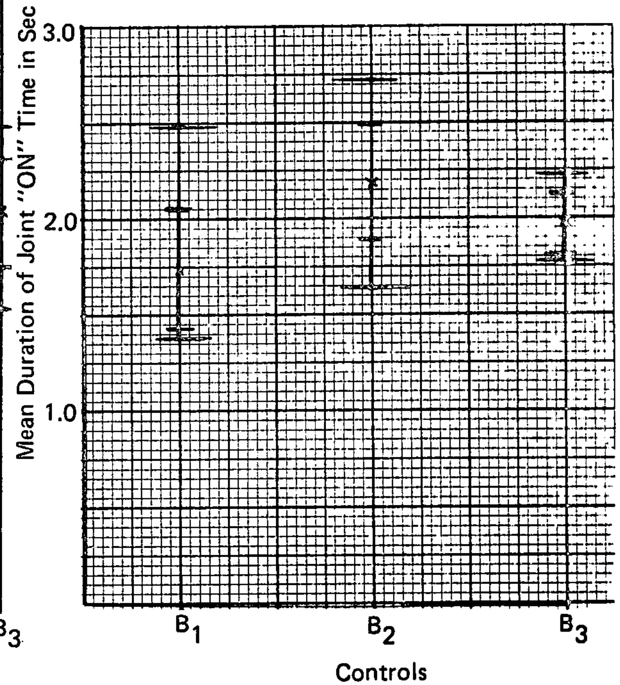

Integrated Joint Movement Time in Sec
600
500
400
300
200
100
A1
A2
A3
Displays

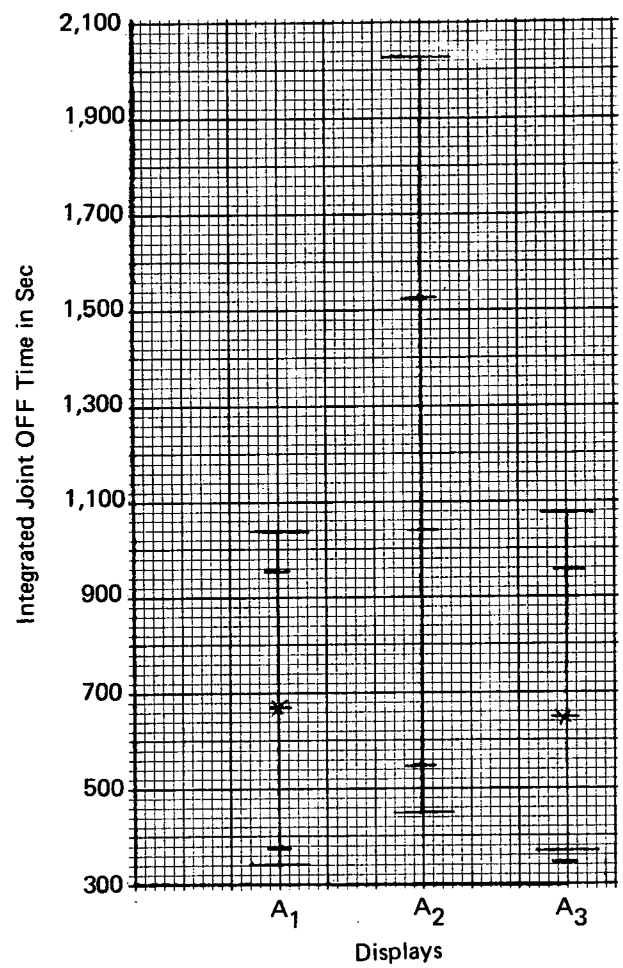

Integrated Joint Movement Time in Sec
600
500
400
300
200
100
B1
B2
B3
Controls

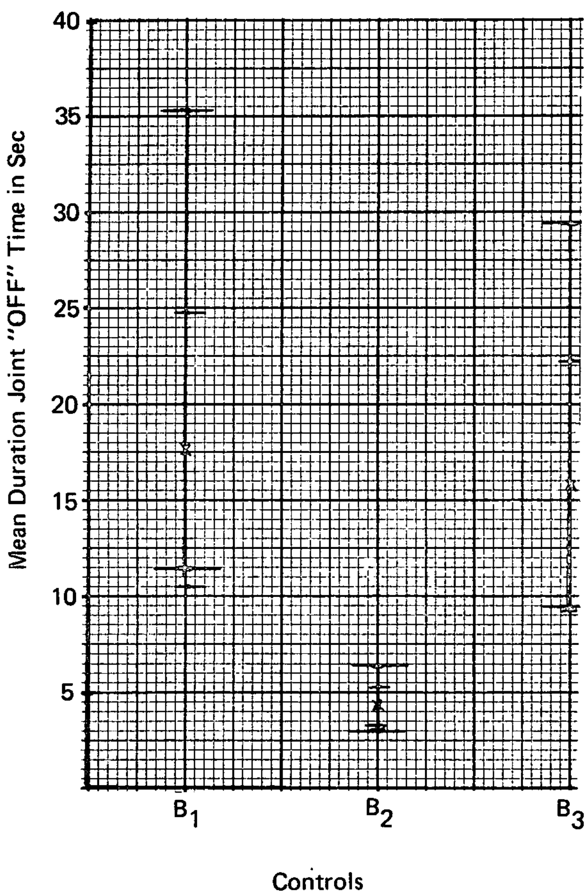

Integrated Joint OFF Time in Sec
2,100
2,000
1,900
1,800
1,700
1,600
1,500
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
A1
A2
A3
Displays

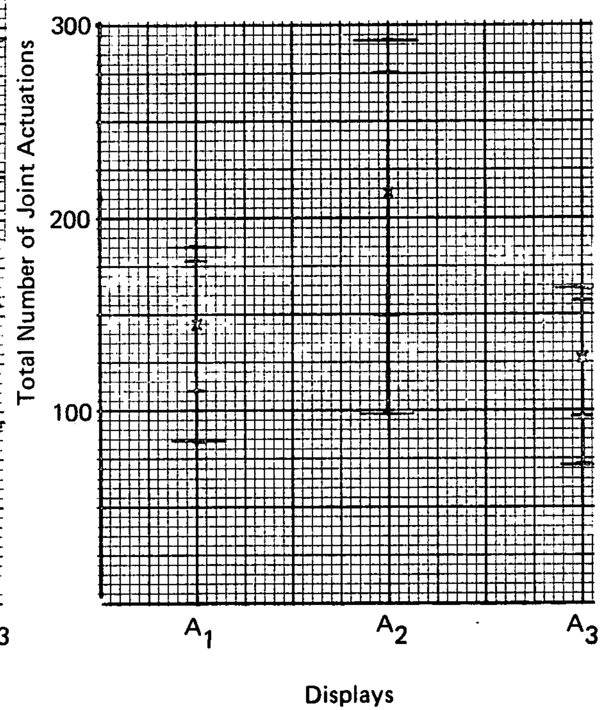

Intregraded Joint OFF Time in Sec
2,100
2,000
1,900
1,800
1,700
1,600
1,500
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
B1
B2
B3
Controls

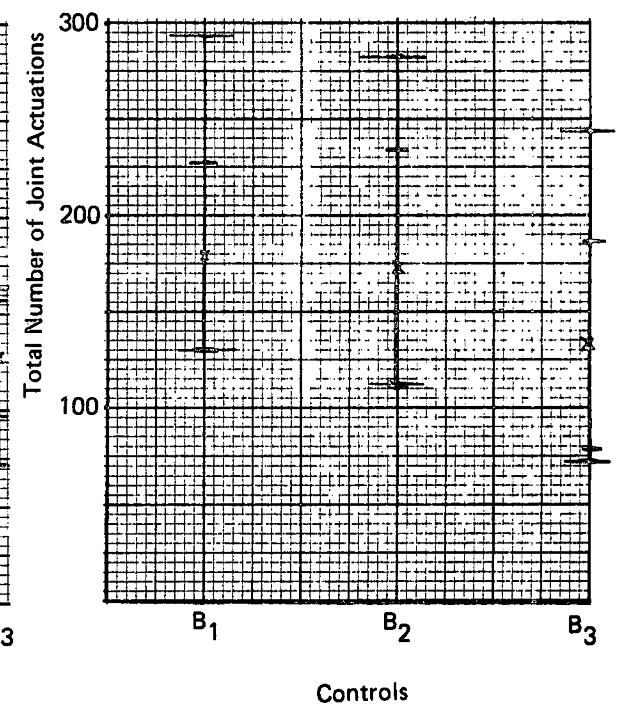

Time Moved: Time Not Moved Ratio
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
B1
B2
B3
Controls

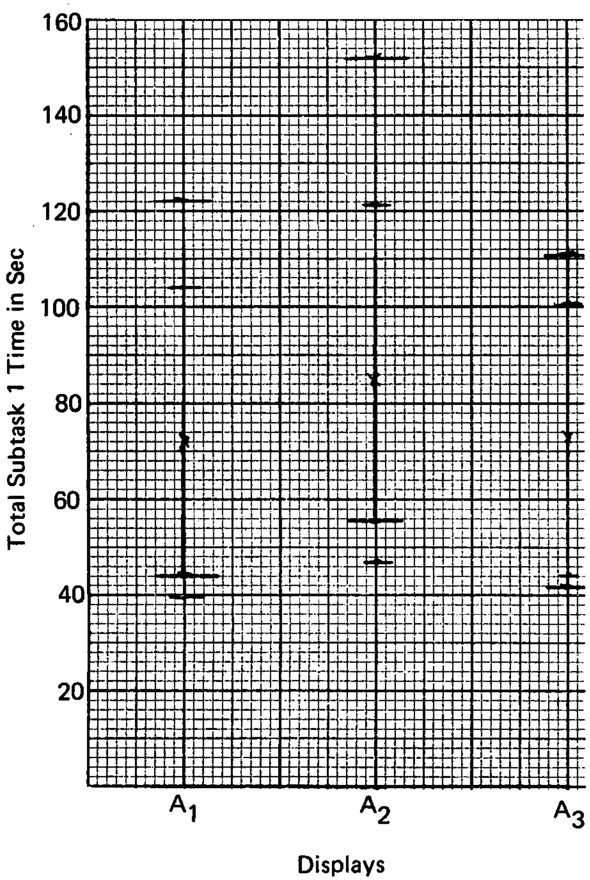

Mean Duration of Joint "ON" Time in Sec
3.0
2.0
1.0
B1
B2
B3
Controls

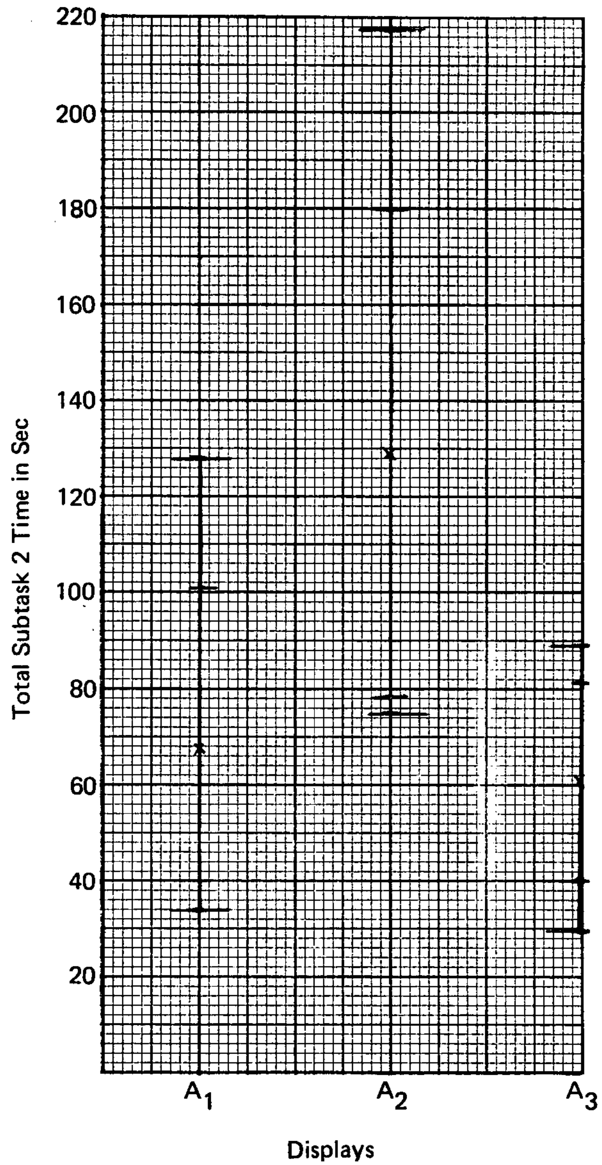

Integrated Joint OFF Time in Sec
2,100
1,900
1,700
1,500
1,300
1,100
900
700
500
300
A_1
A_2
A_3
Displays

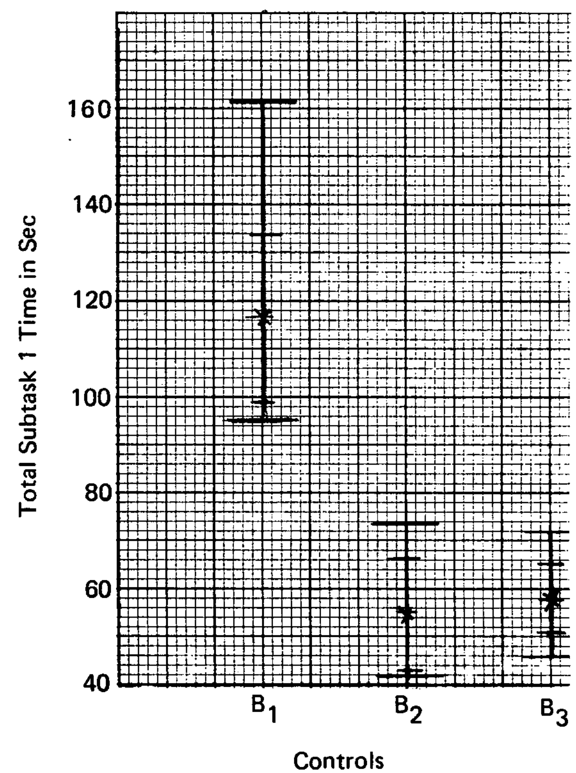

Mean Duration Joint "OFF" Time in Sec
40
35
30
25
20
15
10
5
B1
B2
B3
Controls

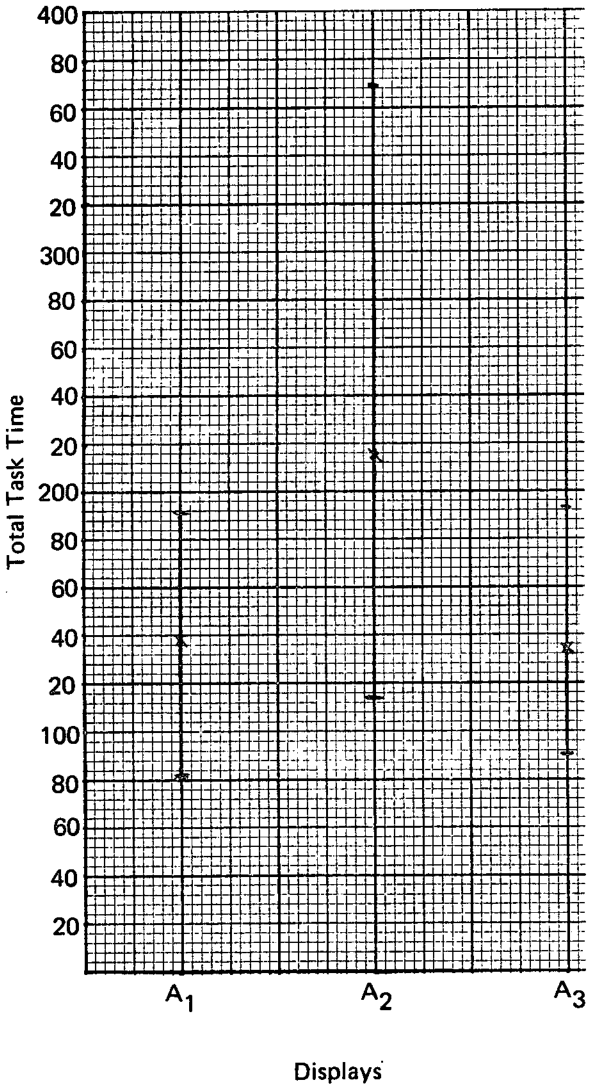

Total Number of Joint Actuations
300
200
100
A1
A2
A3
Displays

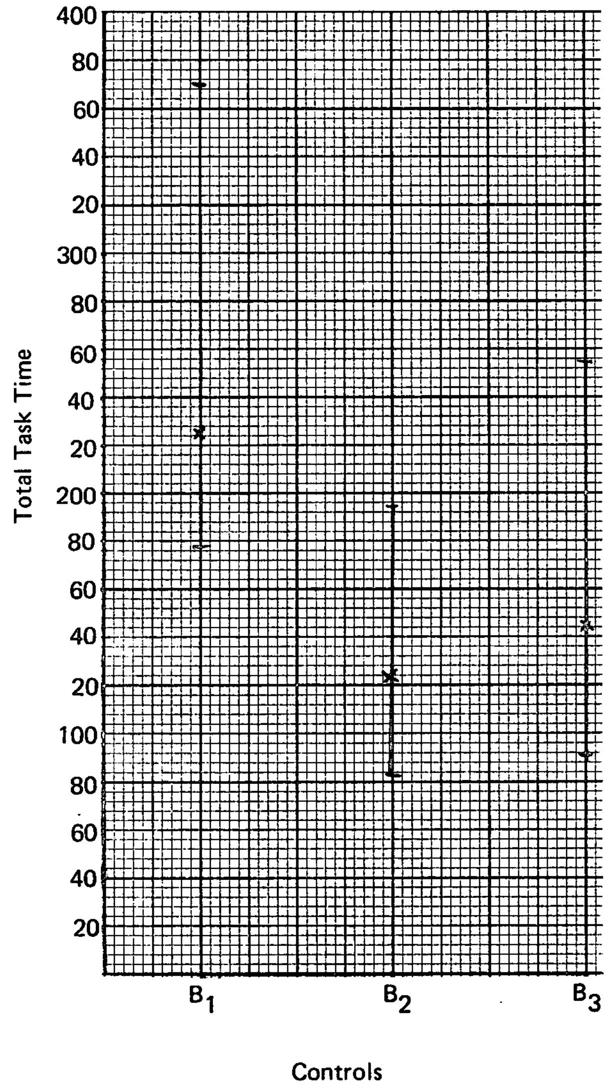

Total Number of Joint Actuations
300
200
100
B1
B2
B3
Controls

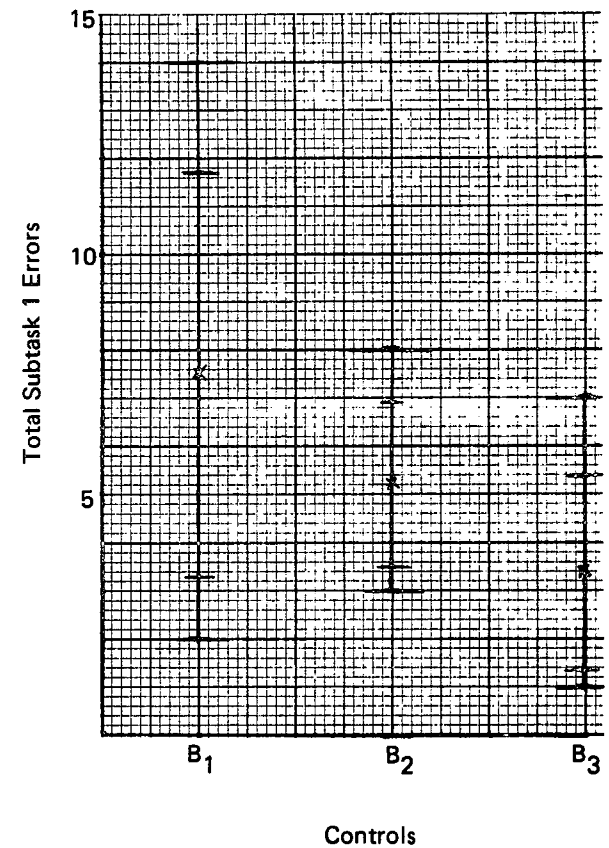

160
140
120
100
80
60
40
20
Total Subtask 1 Time in Sec
A_1
A_2
A_3
Displays

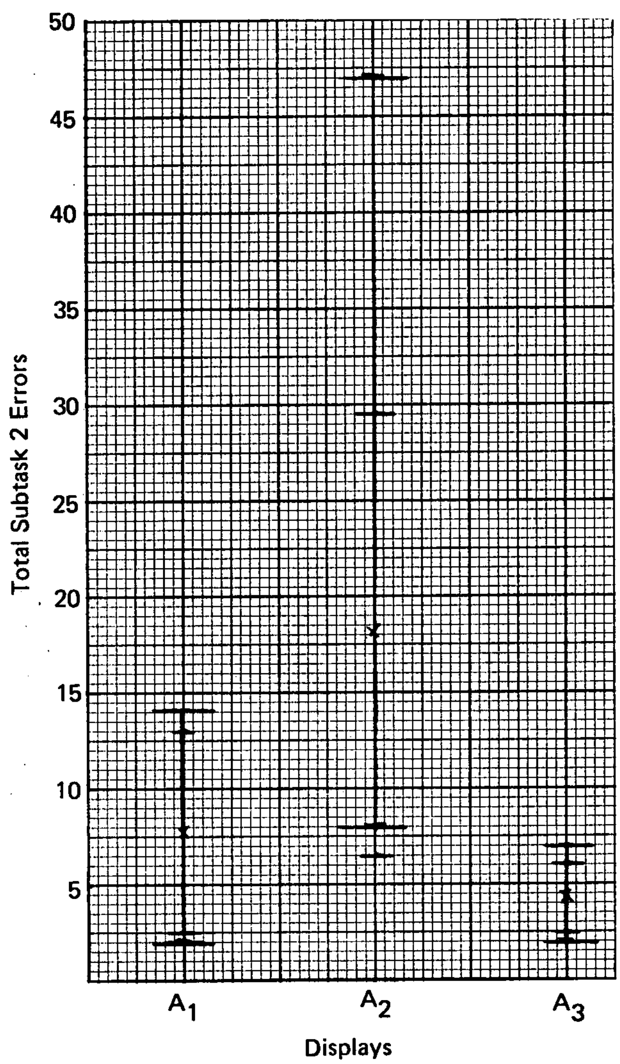

220
200
180
160
140
120
100
80
60
40
20
Total Subtask 2 Time in Sec
A_1
A_2
A_3
Displays

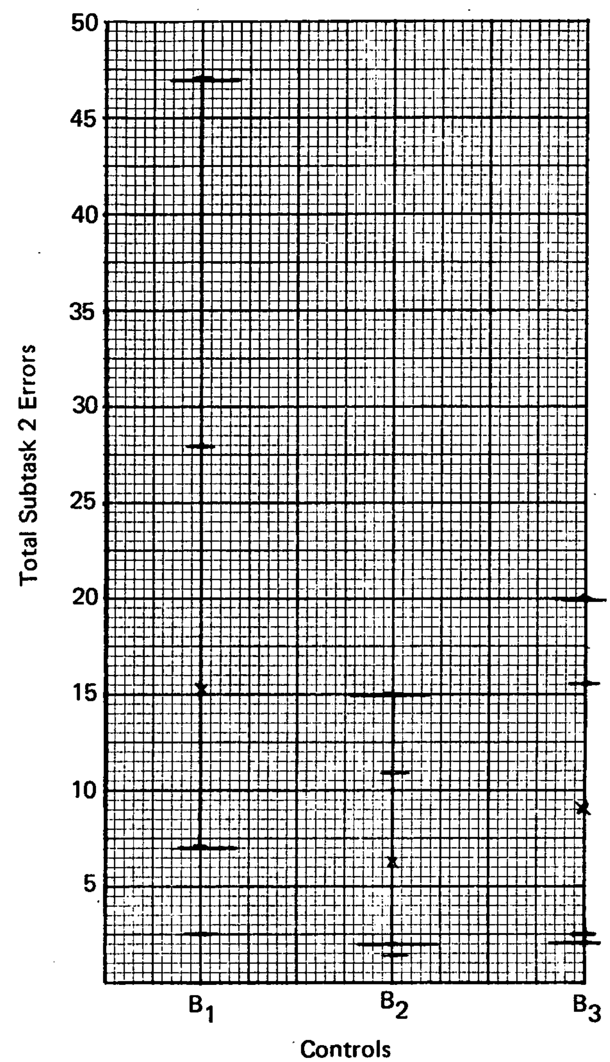

160
140
120
100
80
60
40
Total Subtask 1 Time in Sec
B_1
B_2
B_3
Controls

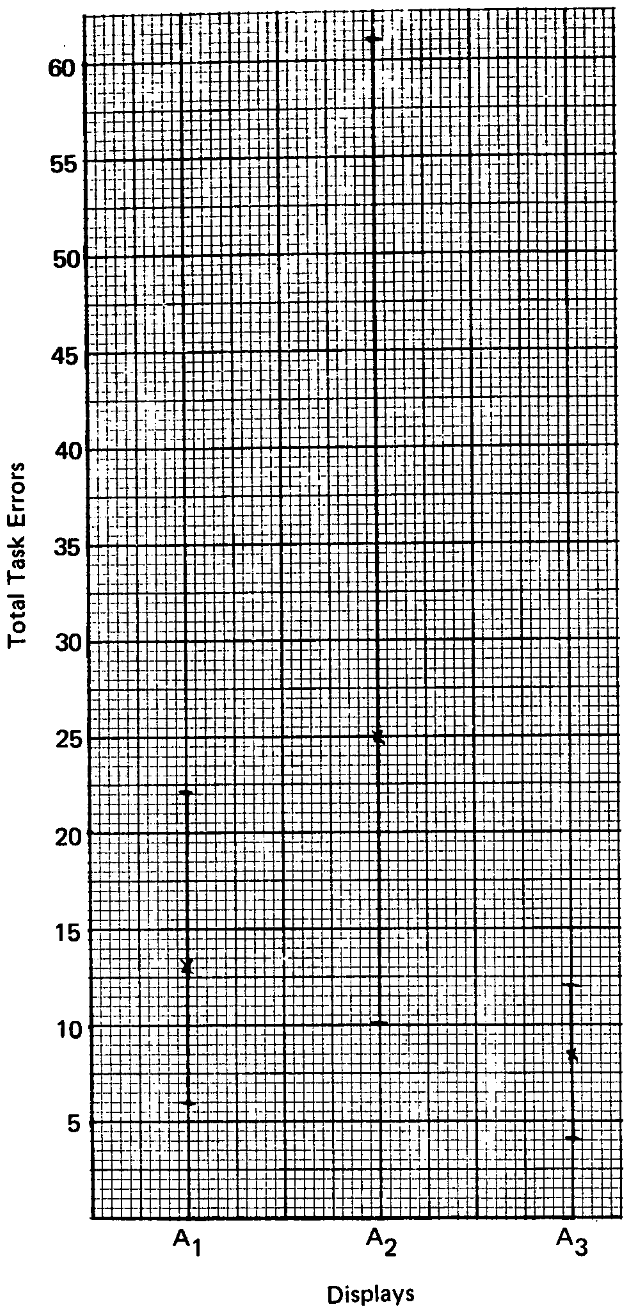

400
80
60
40
20
300
80
60
40
20
200
80
60
40
20
100
80
60
40
20
Total Task Time
A1
A2
A3
Displays


400
80
60
40
20
300
80
60
40
20
200
80
60
40
20
100
80
60
40
20
Total Task Time
B1
B2
B3
Controls

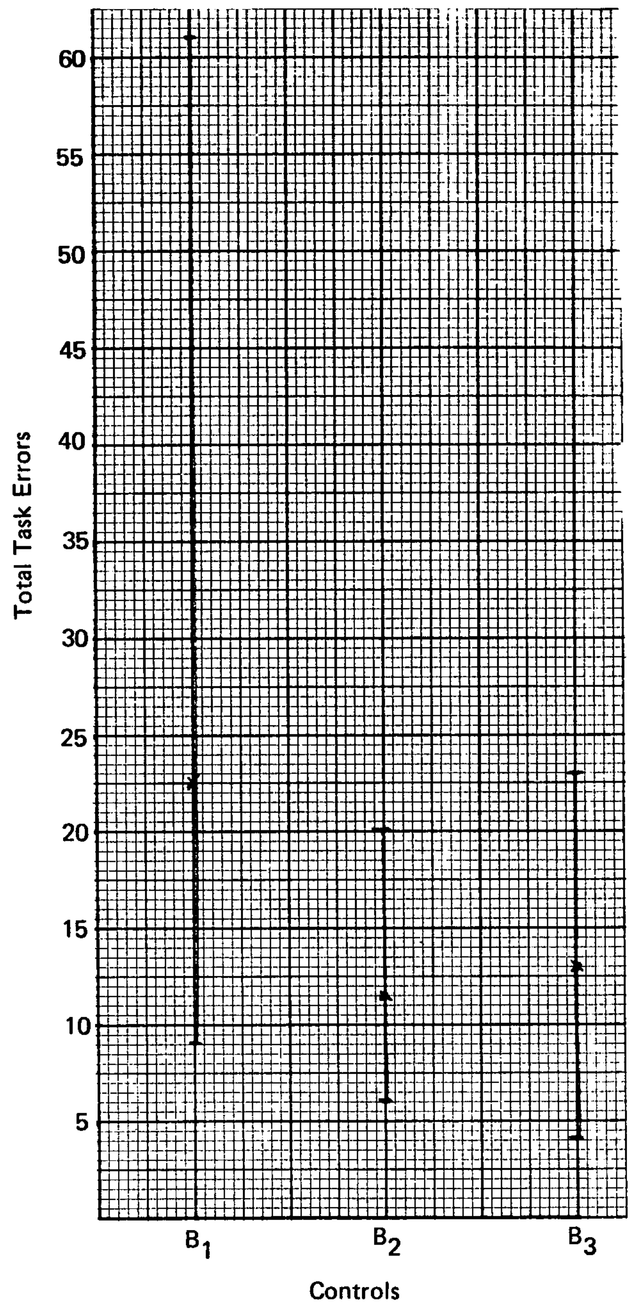

15
10
5
Total Subtask 1 Errors
B1
B2
B3
Controls


Total Subtask 2 Errors
50
45
40
35
30
25
20
15
10
5
A1
A2
A3
Displays


Total Subtask 2 Errors
50
45
40
35
30
25
20
15
10
5
B1
B2
B3
Controls



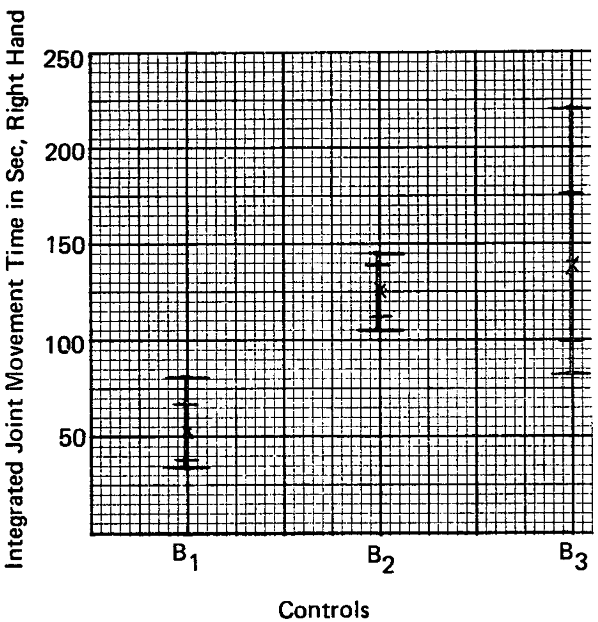
Total Task Errors
60
55
50
45
40
35
30
25
20
15
10
5
A_1
A_2
A_3
Displays

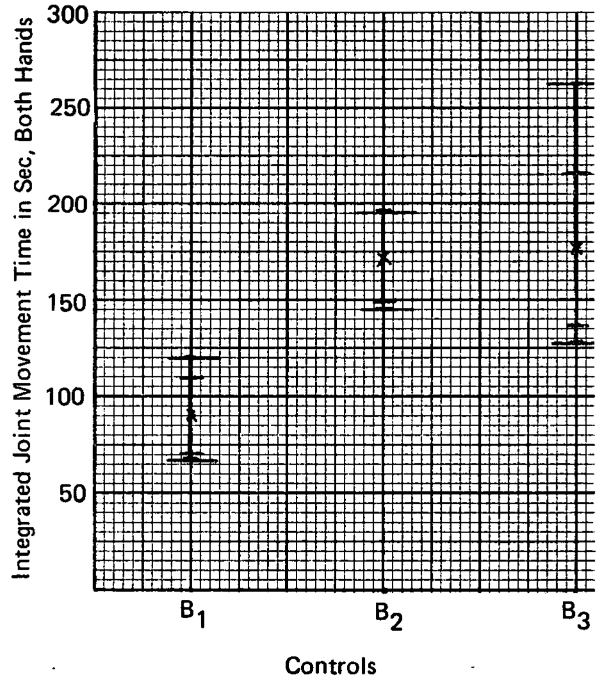


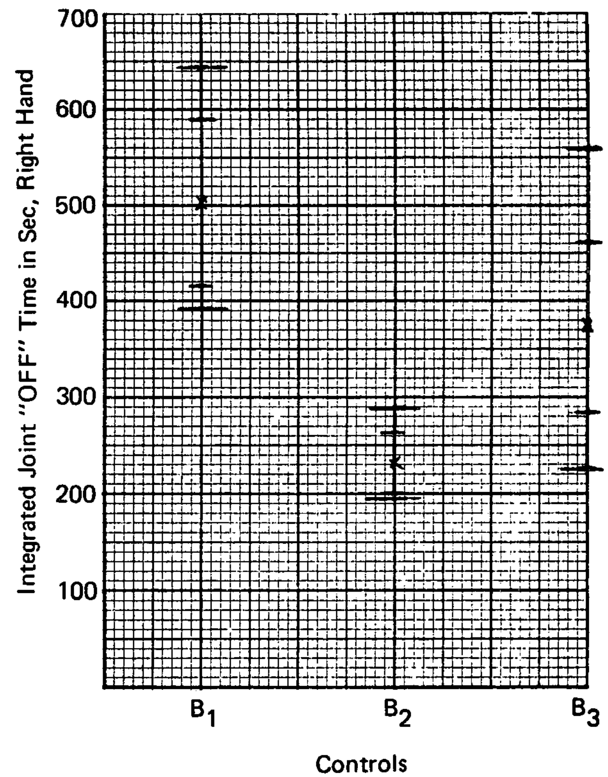
Total Task Errors
60
55
50
45
40
35
30
25
20
15
10
5
B_1
B_2
B_3
Controls

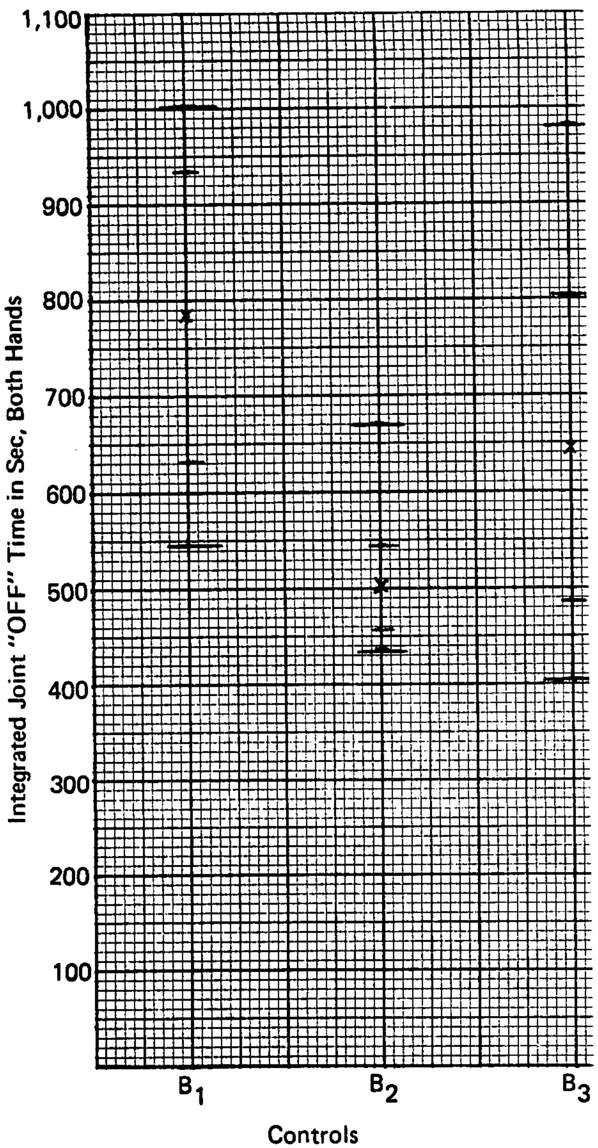
MANIPULATION EXPERIMENT E5: FLUID COUPLING

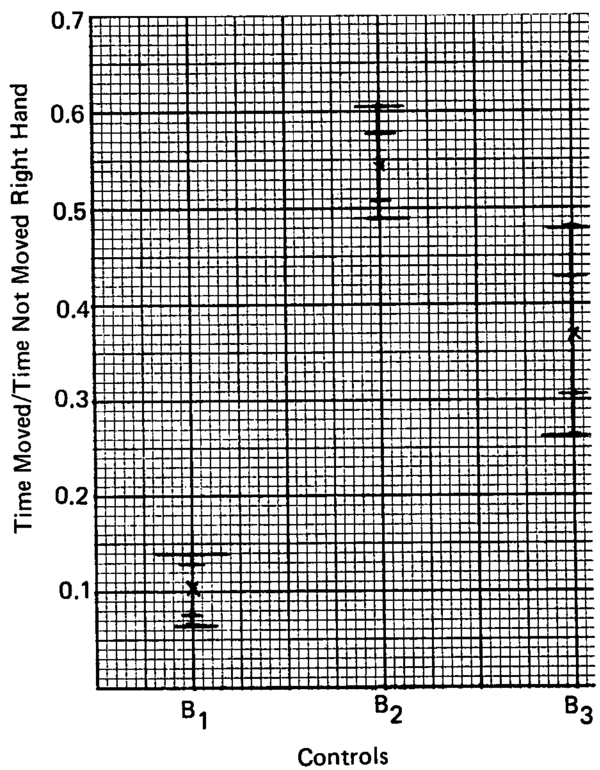
GRAPHICAL PRESENTATION OF
SIGNIFICANT RESULTS

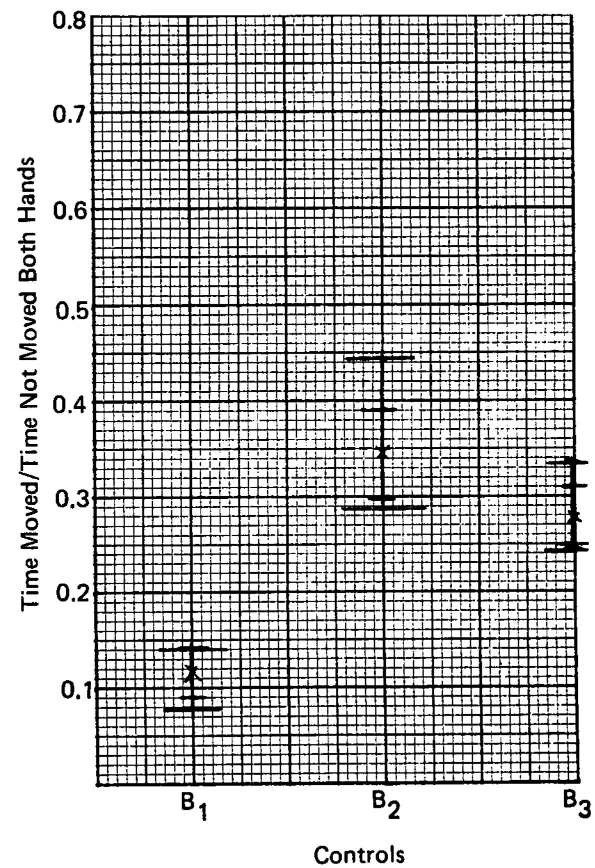

Integrated Joint Movement Time in Sec, Right Hand
250
200
150
100
50
B_1
B_2
B_3
Controls

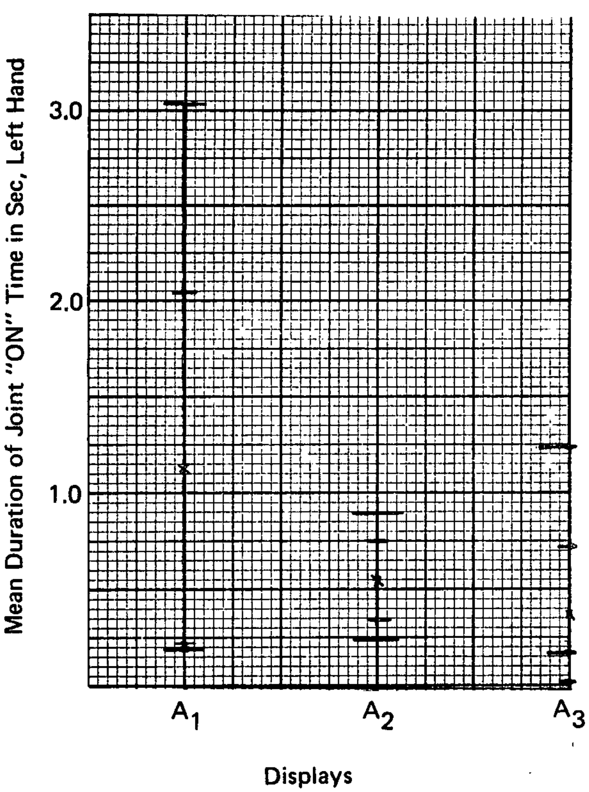

Integrated Joint Movement Time in Sec, Both Hands
300
250
200
150
100
50
B_1
B_2
B_3
Controls

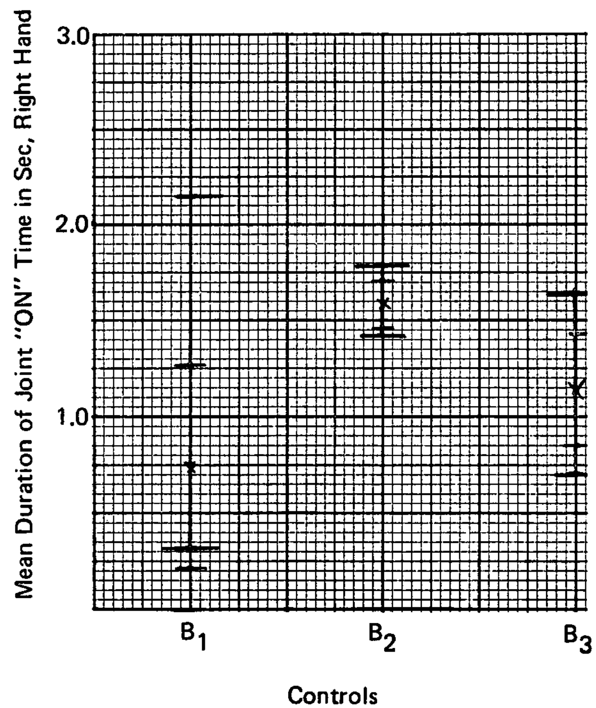

Integrated Joint "OFF" Time in Sec, Right Hand
700
600
500
400
300
200
100
B_1
B_2
B_3
Controls

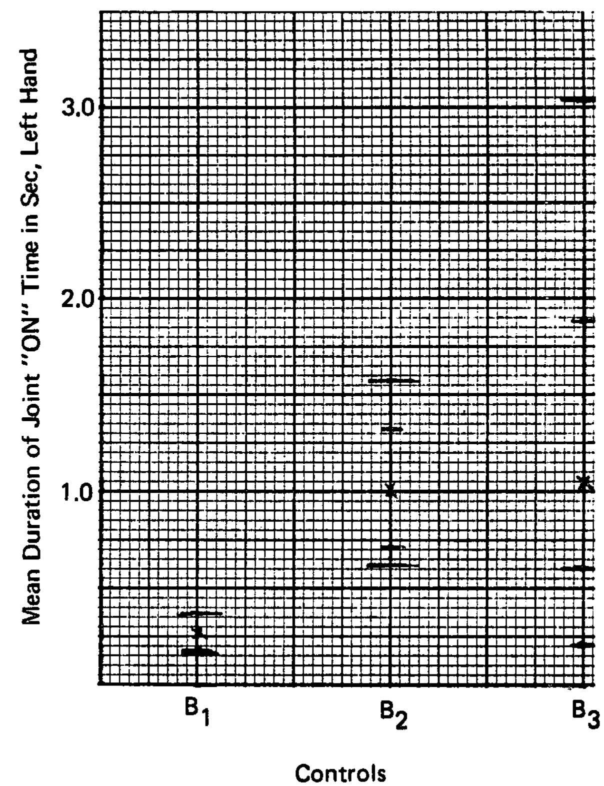

1,100
1,000
900
800
700
600
500
400
300
200
100
Integrated Joint "OFF" Time in Sec, Both Hands
B_1
B_2
B_3
Controls

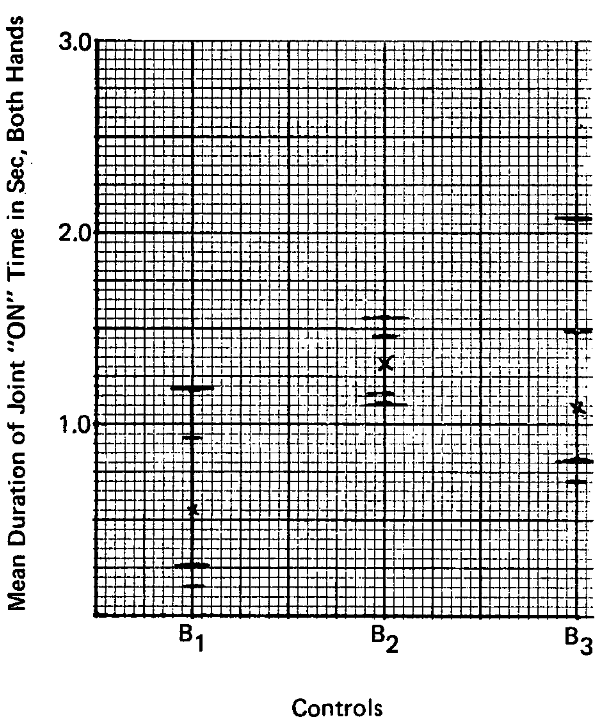

0.7
0.6
0.5
0.4
0.3
0.2
0.1
Time Moved/Time Not Moved Right Hand
B_1
B_2
B_3
Controls

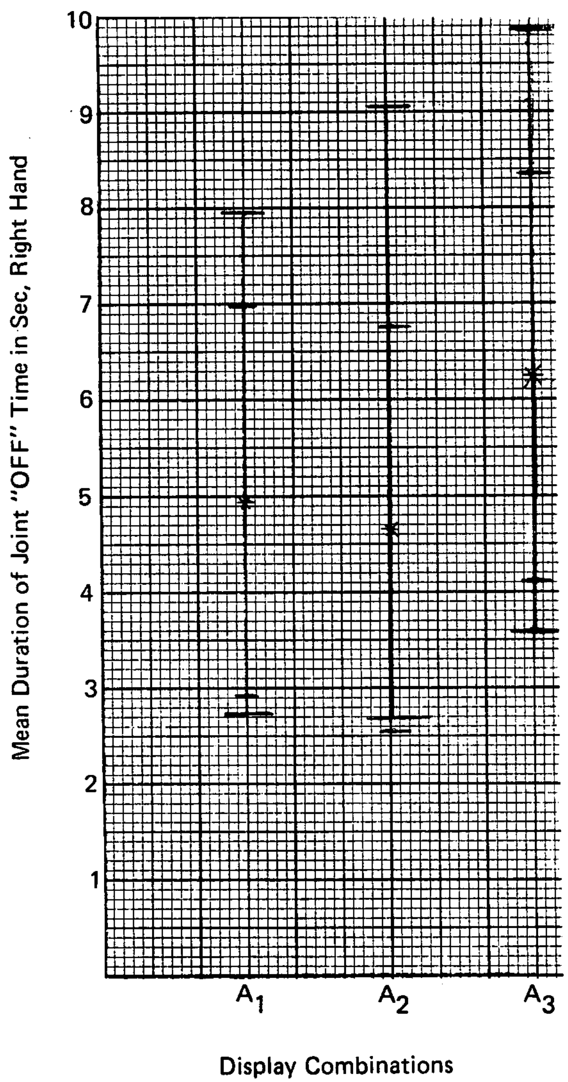

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Time Moved/Time Not Moved Both Hands
B_1
B_2
B_3
Controls

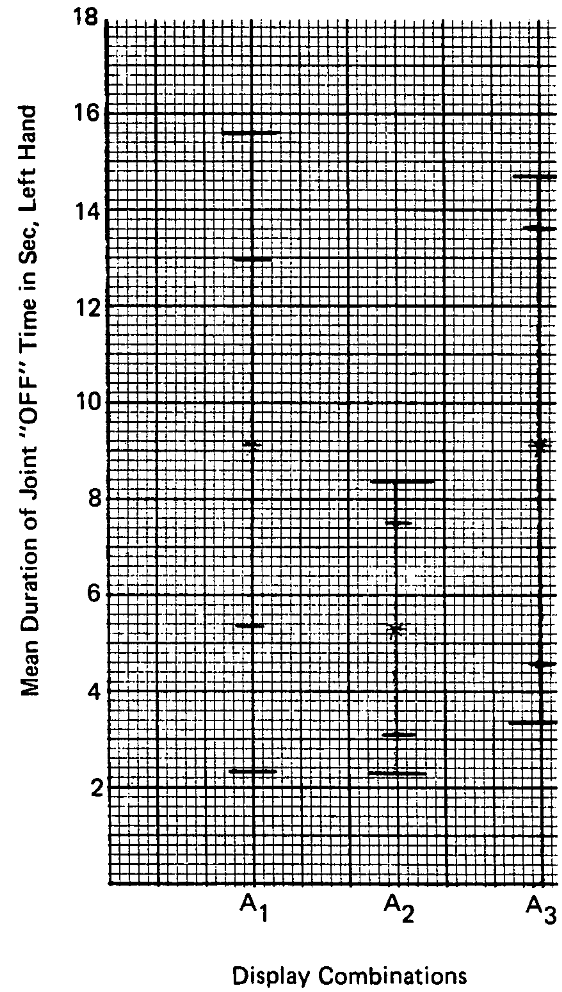

Mean Duration of Joint "ON" Time in Sec, Left Hand
3.0
2.0
1.0
A1
A2
A3
Displays

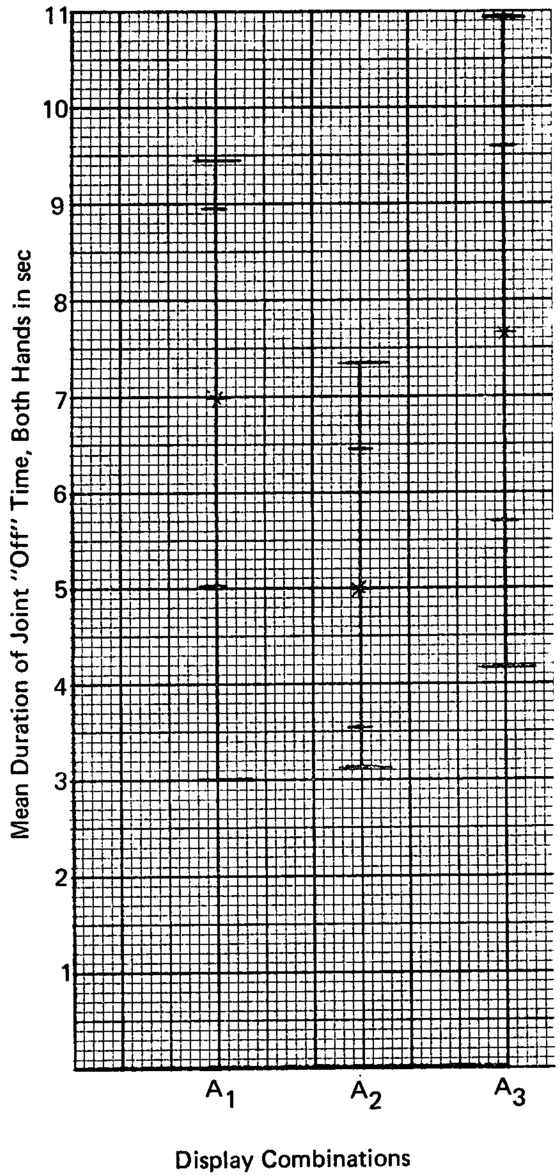

Mean Duration of Joint "ON" Time in Sec, Right Hand
3.0
2.0
1.0
B1
B2
B3
Controls


Mean Duration of Joint "ON" Time in Sec, Left Hand
3.0
2.0
1.0
B1
B2
B3
Controls

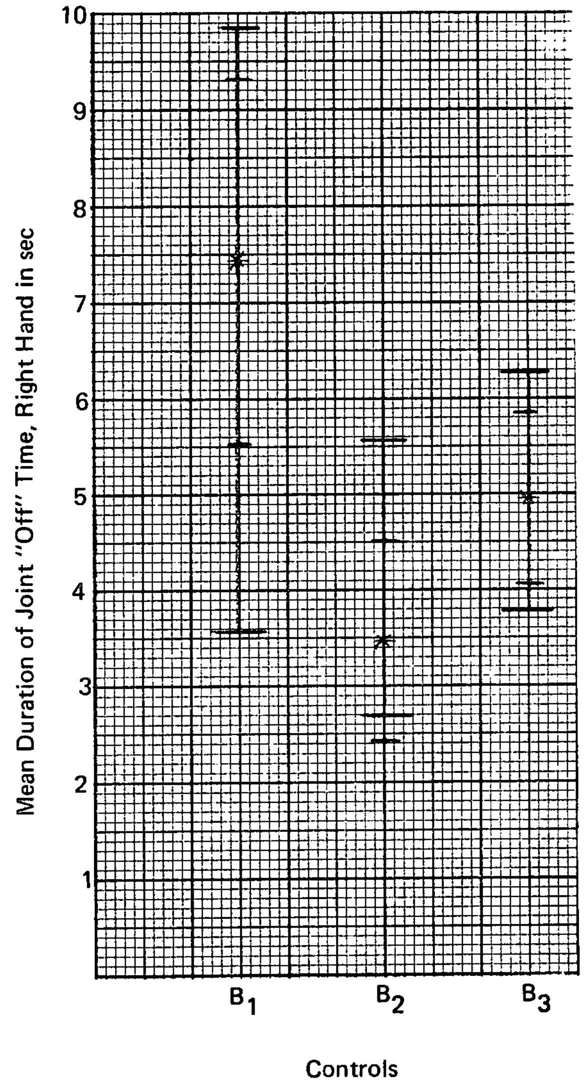

Mean Duration of Joint "ON" Time in Sec, Both Hands
3.0
2.0
1.0
B1
B2
B3
Controls


Mean Duration of Joint "OFF" Time in Sec, Right Hand
10
9
8
7
6
5
4
3
2
1
A1
A2
A3
Display Combinations

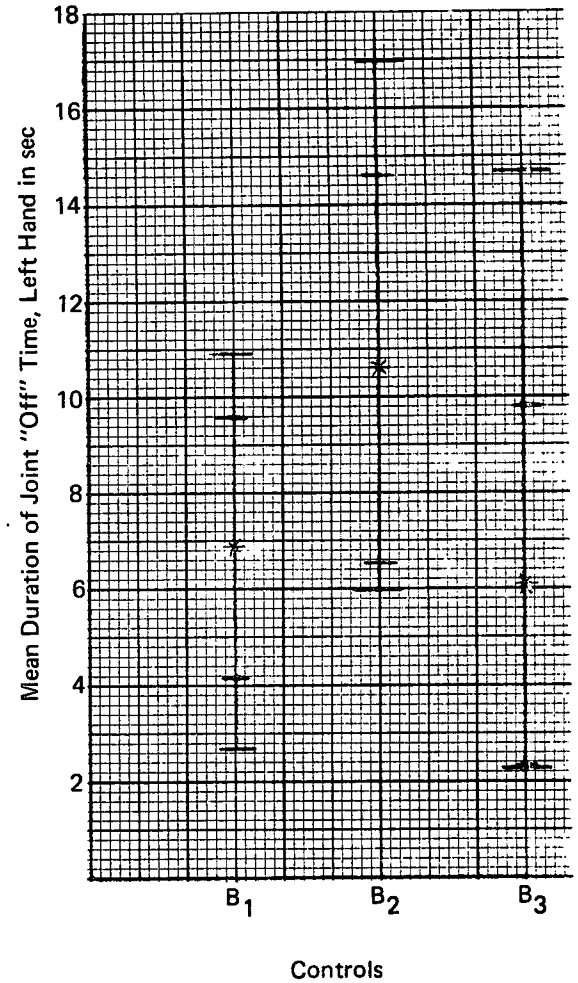

Mean Duration of Joint "OFF" Time in Sec, Left Hand
18
16
14
12
10
8
6
4
2
A1
A2
A3
Display Combinations



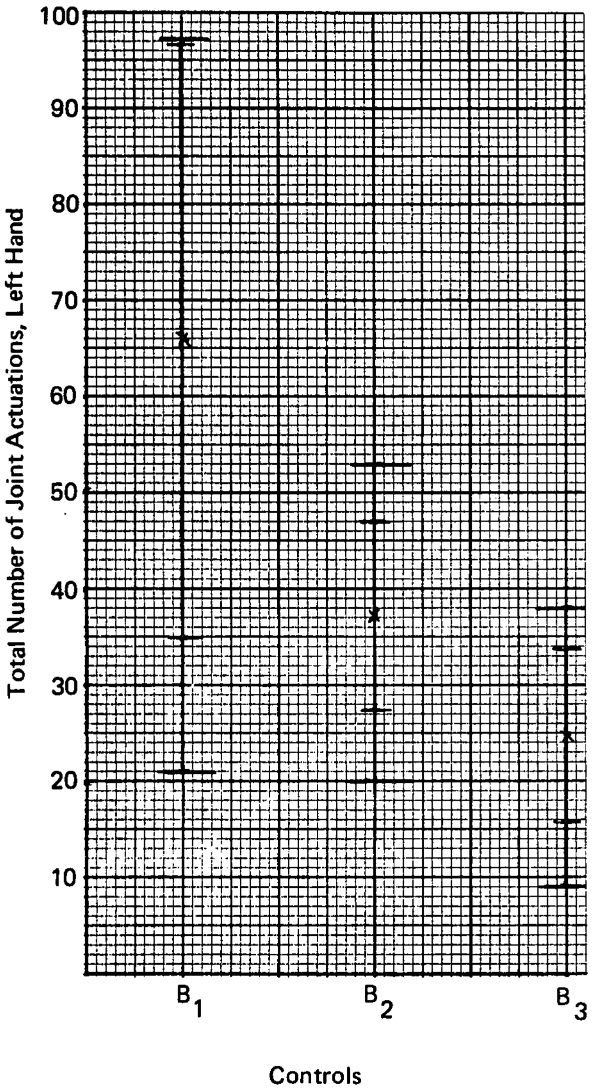
Mean Duration of Joint "Off" Time, Both Hands in sec
1
2
3
4
5
6
7
8
9
10
11
A1
A2
A3
Display Combinations



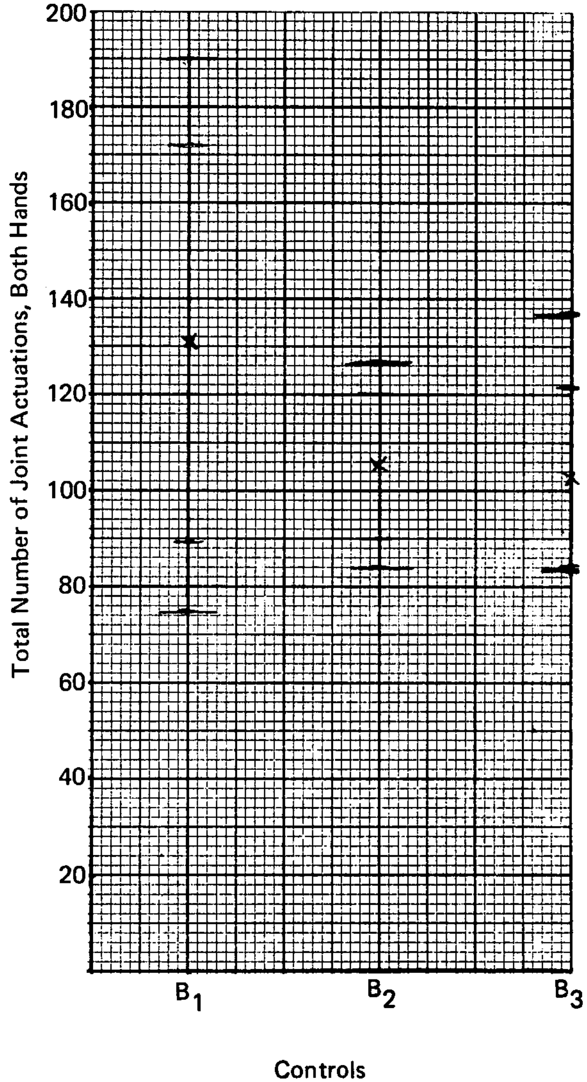
Mean Duration of Joint "Off" Time, Right Hand in sec
1
2
3
4
5
6
7
8
9
10
B1
B2
B3
Controls



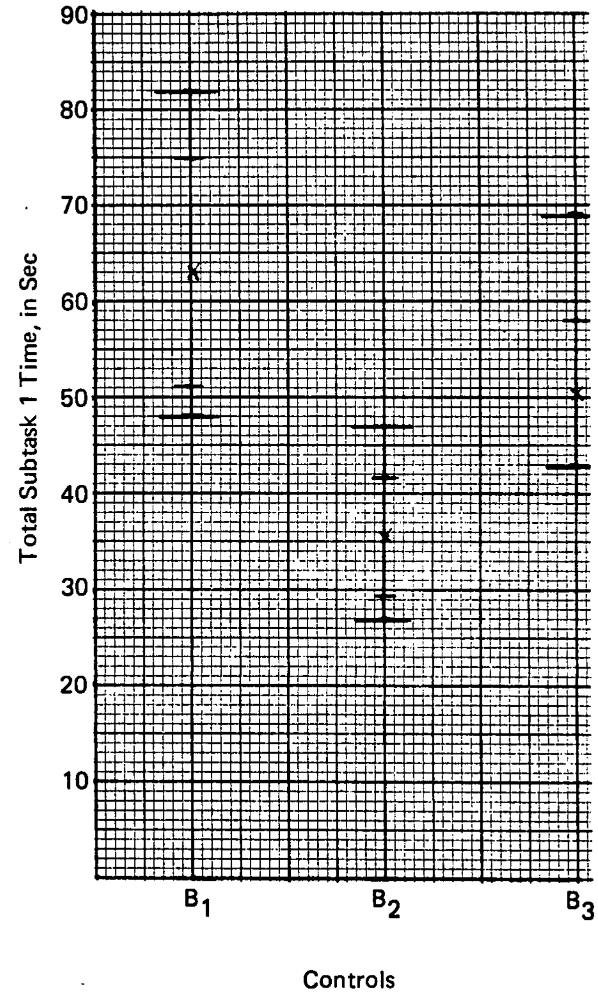
Mean Duration of Joint "Off" Time, Left Hand in sec
2
4
6
8
10
12
14
16
18
B1
B2
B3
Controls



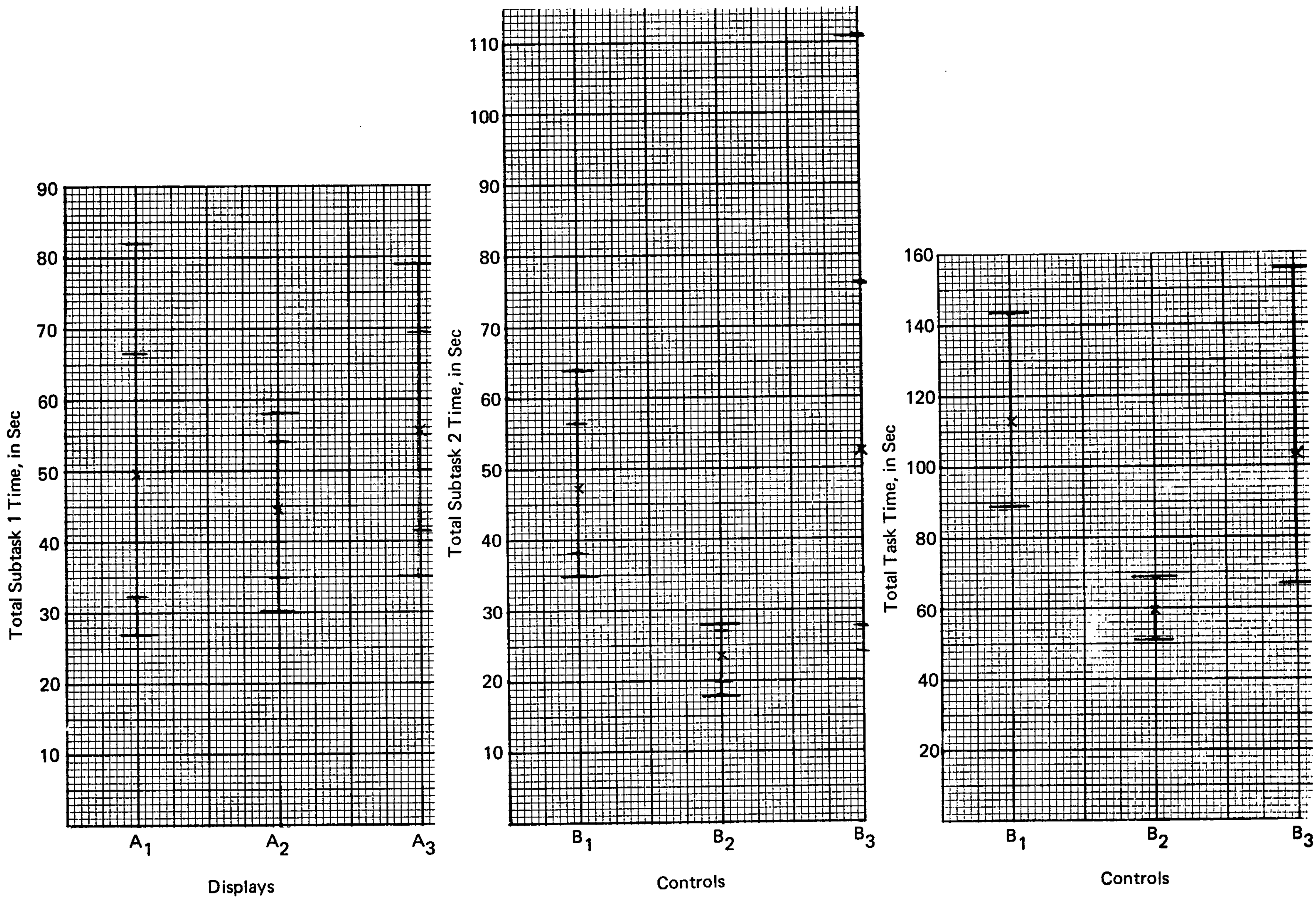
Total Number of Joint Actuations, Left Hand
100
90
80
70
60
50
40
30
20
10
B_1
B_2
B_3
Controls



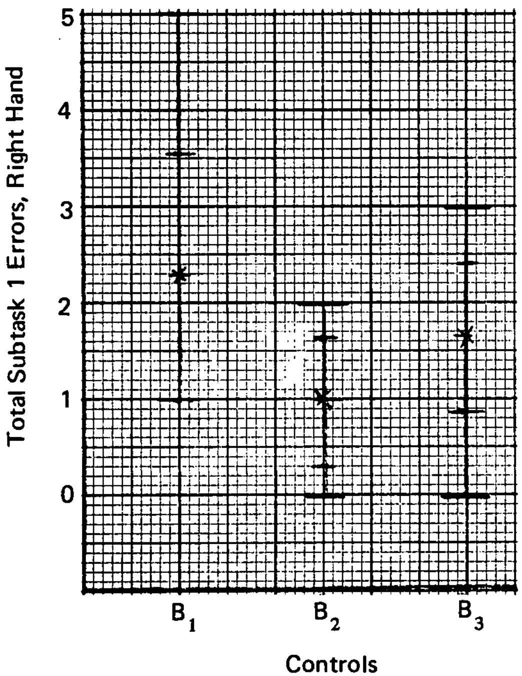
Total Number of Joint Actuations, Both Hands
200
180
160
140
120
100
80
60
40
20
B_1
B_2
B_3
Controls



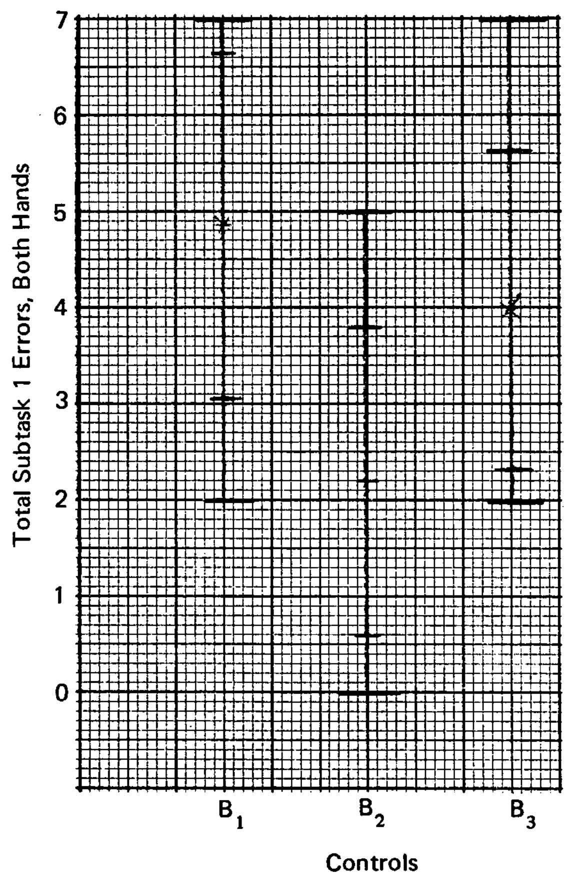
Total Subtask 1 Time, in Sec
90
80
70
60
50
40
30
20
10
B_1
B_2
B_3
Controls



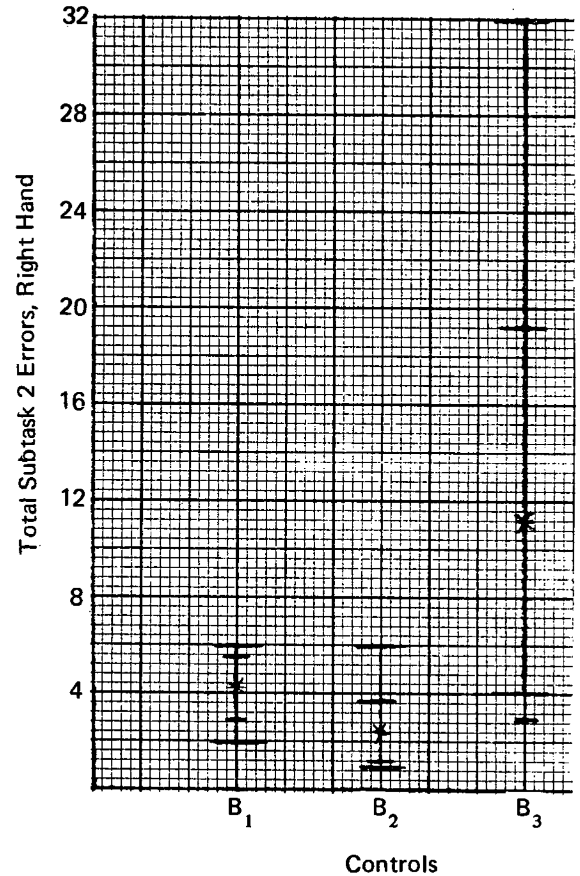
Total Subtask 1 Time, in Sec
90
80
70
60
50
40
30
20
10
A1
A2
A3
Displays
Total Subtask 2 Time, in Sec
110
100
90
80
70
60
50
40
30
20
10
B1
B2
B3
Controls
Total Task Time, in Sec
160
140
120
100
80
60
40
20
B1
B2
B3
Controls



Total Subtask 1 Errors, Right Hand
5
4
3
2
1
0
B1
B2
B3
Controls

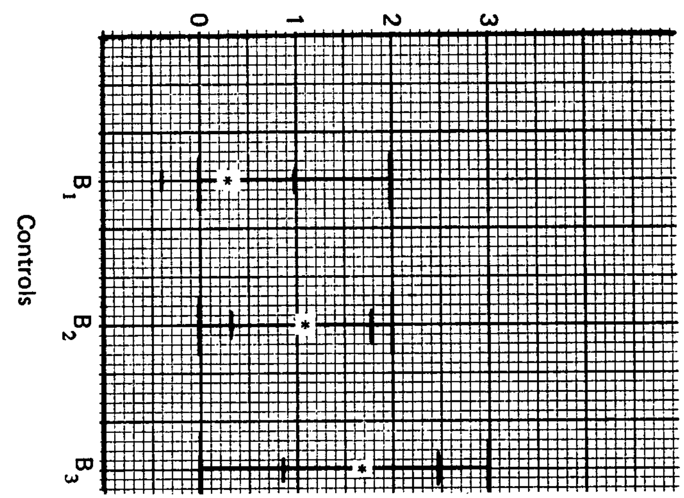


Total Subtask 1 Errors, Both Hands
7
6
5
4
3
2
1
0
B1
B2
B3
Controls

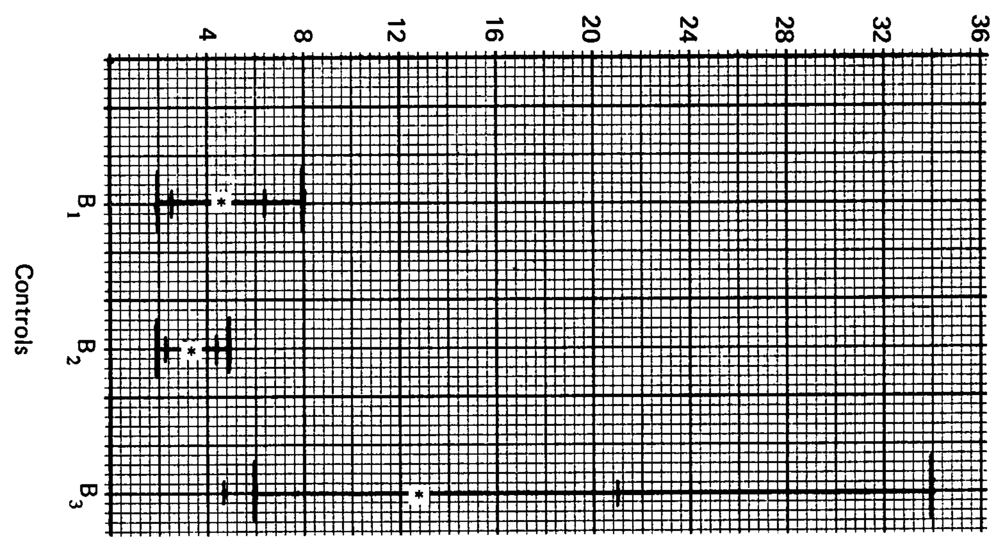


Total Subtask 2 Errors, Right Hand
32
28
24
20
16
12
8
4
B1
B2
B3
Controls

Total Subtask 2 Errors, Left Hand

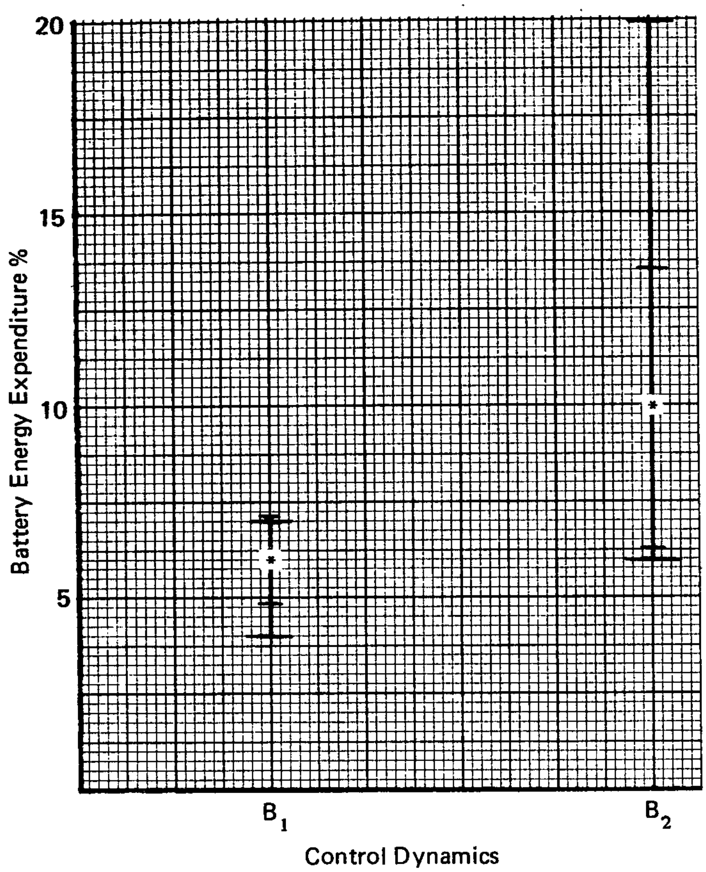


Total Subtask 2 Errors, Both Hands

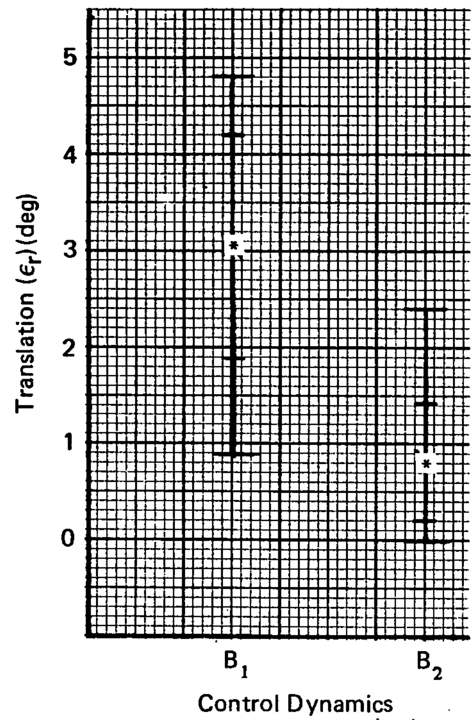


MANEUVERING EXPERIMENT E6: MANEUVERING AND DOCKING

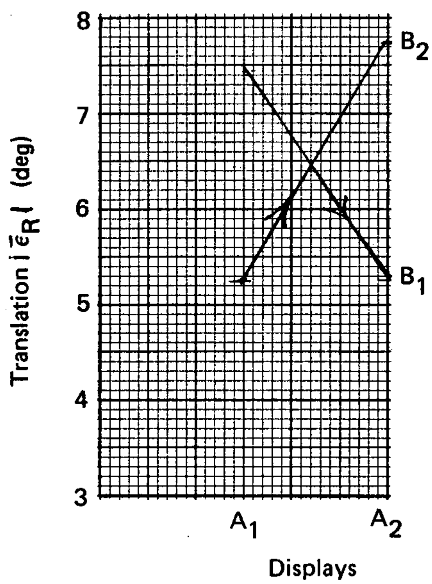
GRAPHICAL PRESENTATION OF
SIGNIFICANT RESULTS



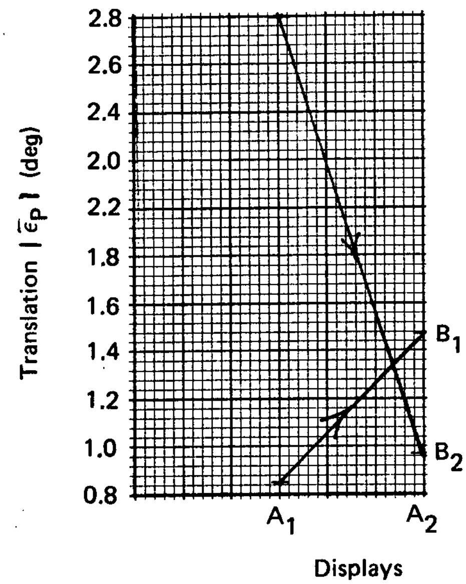
20
15
10
5
Battery Energy Expenditure %
B1
B2
Control Dynamics



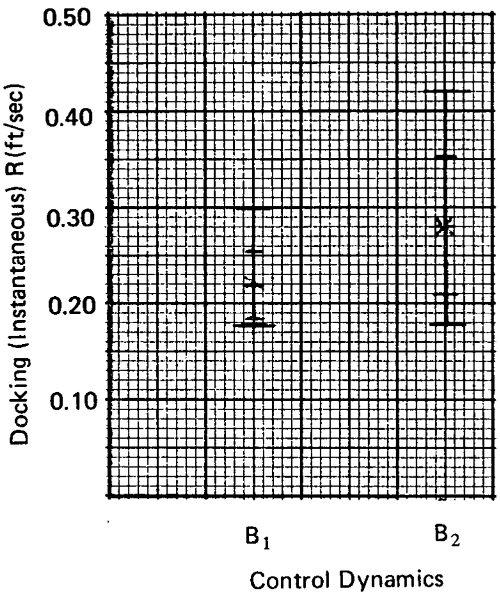
5
4
3
2
1
0
Translation (ϵ_r)(deg)
B1
B2
Control Dynamics

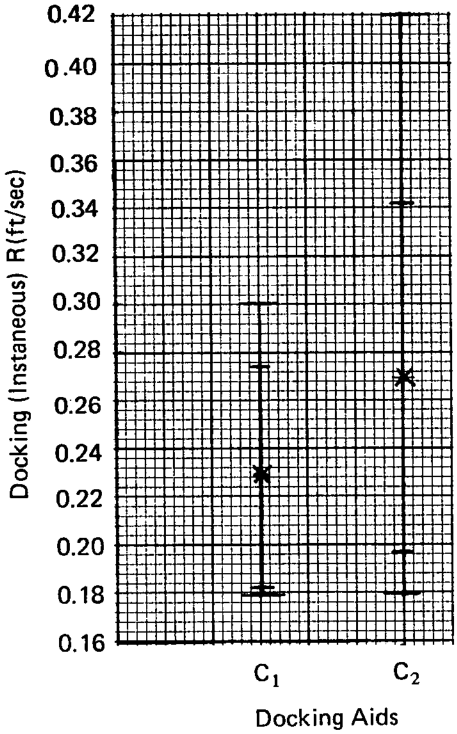


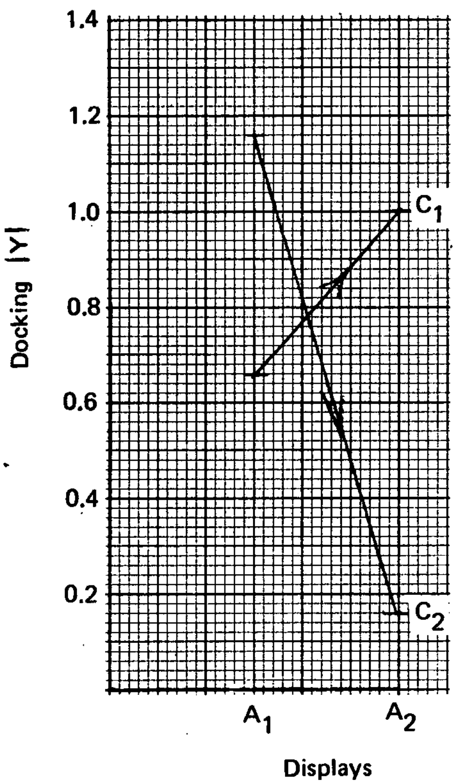
8
7
6
5
4
3
B2
B1
A1
A2
Translation |$\bar{\epsilon}_R$| (deg)
Displays

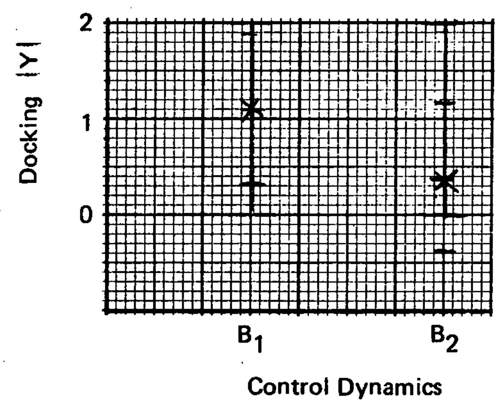


2.8
2.6
2.4
2.0
2.2
1.8
1.6
1.4
1.2
1.0
0.8
B1
B2
A1
A2
Translation |$\bar{\epsilon}_P$| (deg)
Displays


Docking (Instantaneous) R (ft/sec)
0.50
0.40
0.30
0.20
0.10
B1
B2
Control Dynamics


Docking (Instaneous) R (ft/sec)
0.42
0.40
0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
C1
C2
Docking Aids


1.4
1.2
1.0
0.8
0.6
0.4
0.2
Docking |Y|
C_1
C_2
A_1
A_2
Displays


2
1
0
Docking |Y|
B_1
B_2
Control Dynamics

APPENDIX D
OPERATOR TRAINING

The assumptions and computational formulae used in the operator training program are presented below:

Assume there are samples X_i from an infinite population which is distributed normally about some mean μ with variance σ^2 for each level of learning.

Let $\hat{\mu}$ and $\hat{\sigma}$ be estimates of the true mean and variance. They may be found from the following formulas:

$$\hat{\mu} = \frac{1}{k} \sum_{i=1}^{k} X_i$$

$$\hat{\sigma}^2 = \frac{1}{k-1} \sum_{i=1}^{k} (X_i - \hat{\mu})^2$$

TESTING VARIANCES THE F TEST

Assume there are two sets of samples each drawn from a normal population with unknown mean and variance. Sample 1 is $x_{11}, \ldots, x_{1k_1}$, while sample 2 is denoted $X_{21}, \ldots, X_{2k_2}$.

Compute the estimate of the means of both samples

$$\hat{\mu}_j = \frac{1}{k_j} \sum_{i=1}^{k_j} X_{ji} \qquad j = 1, 2$$

Next, compute the estimate of the variances of each sample

$$\hat{\sigma}_j^2 = \frac{1}{k_j - 1} \sum_{i=1}^{k_j} (X_{ji} - \mu_j) \qquad j = 1, 2$$

It is known that

$$A = \frac{\hat{\sigma}_1^2}{\hat{\sigma}_2^2}$$

is distributed $F(k_1\text{-}1, k_2\text{-}1)$ if $\sigma_1^2 = \sigma_2^2$.

In order to test the hypothesis, a confidence level must be selected (x often chosen as 0.05). α is Type I error - the error of rejecting the hypothesis when it is true. Therefore, to accept the hypothesis A must lie in the following range.

$$F_{\left(1-\frac{\alpha}{2}\right)}(k_1-1, k_2-1) < A < F_{\frac{\alpha}{2}}(k_1-1, k_2-1)$$

otherwise the conclusion is that $\sigma_1 \neq \sigma_2$.

TESTING MEANS THE t TEST

Using the same assumptions as in the preceding section, with the additional assumption $\sigma_1 = \sigma_2 = \sigma$

$$B = \frac{\mu_1 - \mu_2}{\hat{\sigma}\sqrt{\frac{1}{k_1} + \frac{1}{k_2}}}$$

is distributed $t\ (k_1 + k_2 - 2)$ if $\mu_1 = \mu_2$ where

$$\hat{\sigma} = \sqrt{\frac{(k_1-1)\,\sigma_1^2 + (k_2-1)\,\sigma_2^2}{k_1 + k_2 - 2}}$$

To accept the hypothesis $\mu_1 = \mu_2$ it is necessary to select a probability of Type I error α. Type I error is the probability of rejecting the hypothesis when it is true. α is often chosen to be 0.05. Therefore, to accept the hypothesis

$$-t_{\frac{\alpha}{2}}(k_1 + k_2 - 2) \leq B \leq t_{\frac{\alpha}{2}}(k_1 + k_2 - 2)$$

or

$$|B| \leq t_{\frac{\alpha}{2}}(k_1 + k_2 - 2)$$

In the event that the conclusion was that $\sigma_1 \neq \sigma_2$, B is computed as follows:

$$B = \frac{\mu_1 - \mu_2}{\sqrt{\frac{\hat{\sigma}_1}{k_1} + \frac{\hat{\sigma}_2}{k_2}}}$$

where the number of degrees of freedom

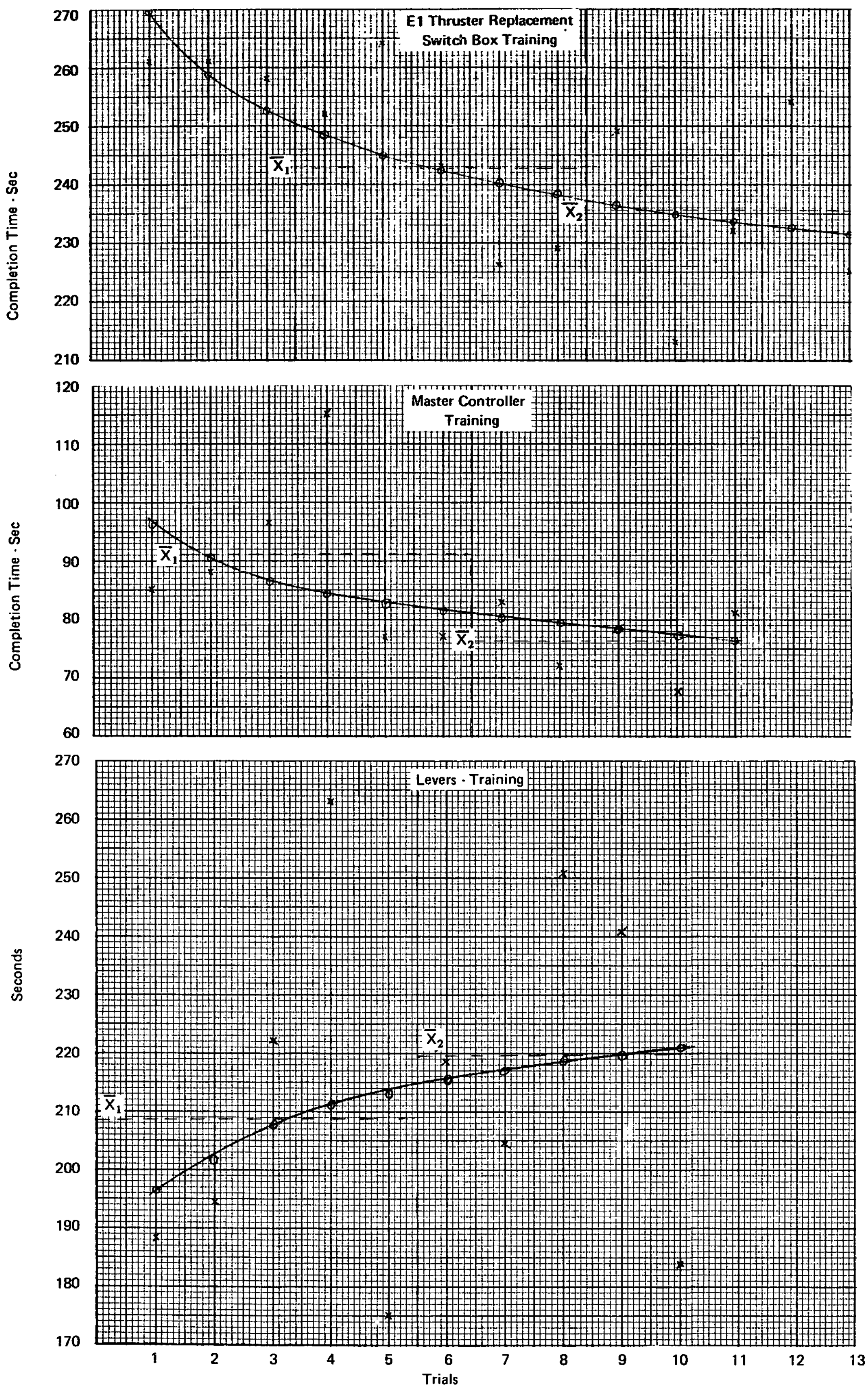
$$N = \frac{\left(\frac{\sigma_1^2}{k_1} + \frac{\sigma_1^2}{k_2}\right)^2}{\frac{\left(\frac{\sigma_1^2}{k_1}\right)^2}{k_1+1} + \frac{\left(\frac{\sigma_1^2}{k_2}\right)^2}{k_2+1}}$$

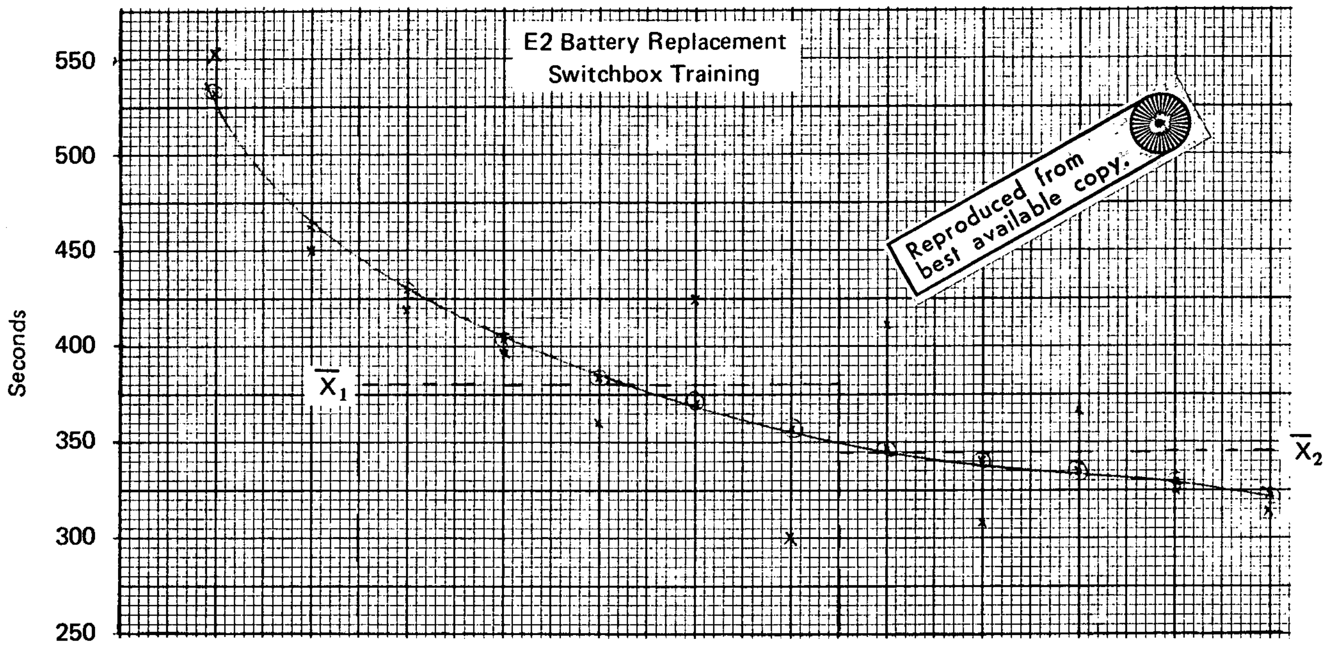
where N is rounded to the nearest integer. Again B, is distributed t (N) if the hypothesis $\mu_1 = \mu_2$ is true. As before, select a probability α of Type I error and accept the hypothesis $\mu_1 = \mu_2$ if

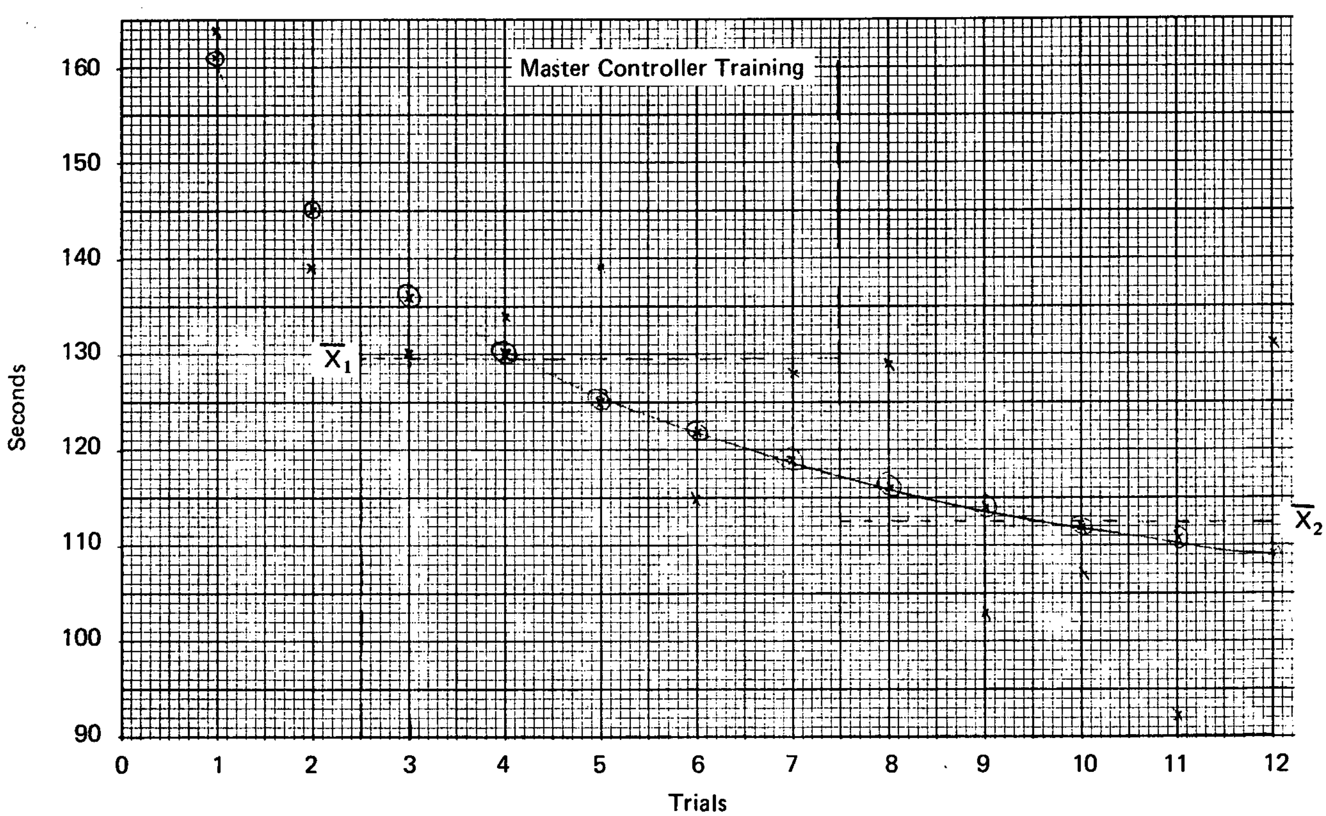
$$-t_{\frac{\alpha}{2}}(N) \leq B \leq t_{\frac{\alpha}{2}}(N)$$

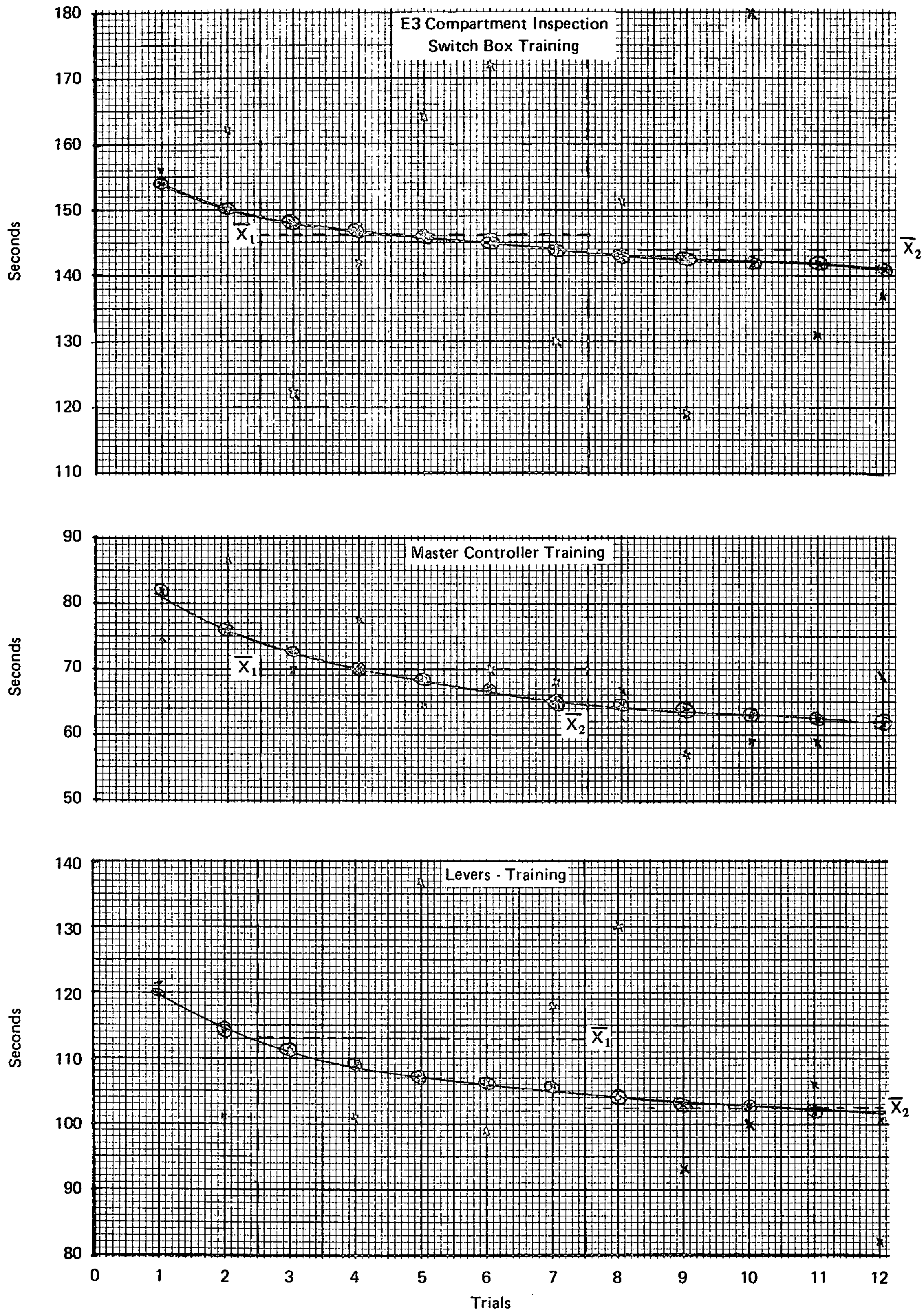
or

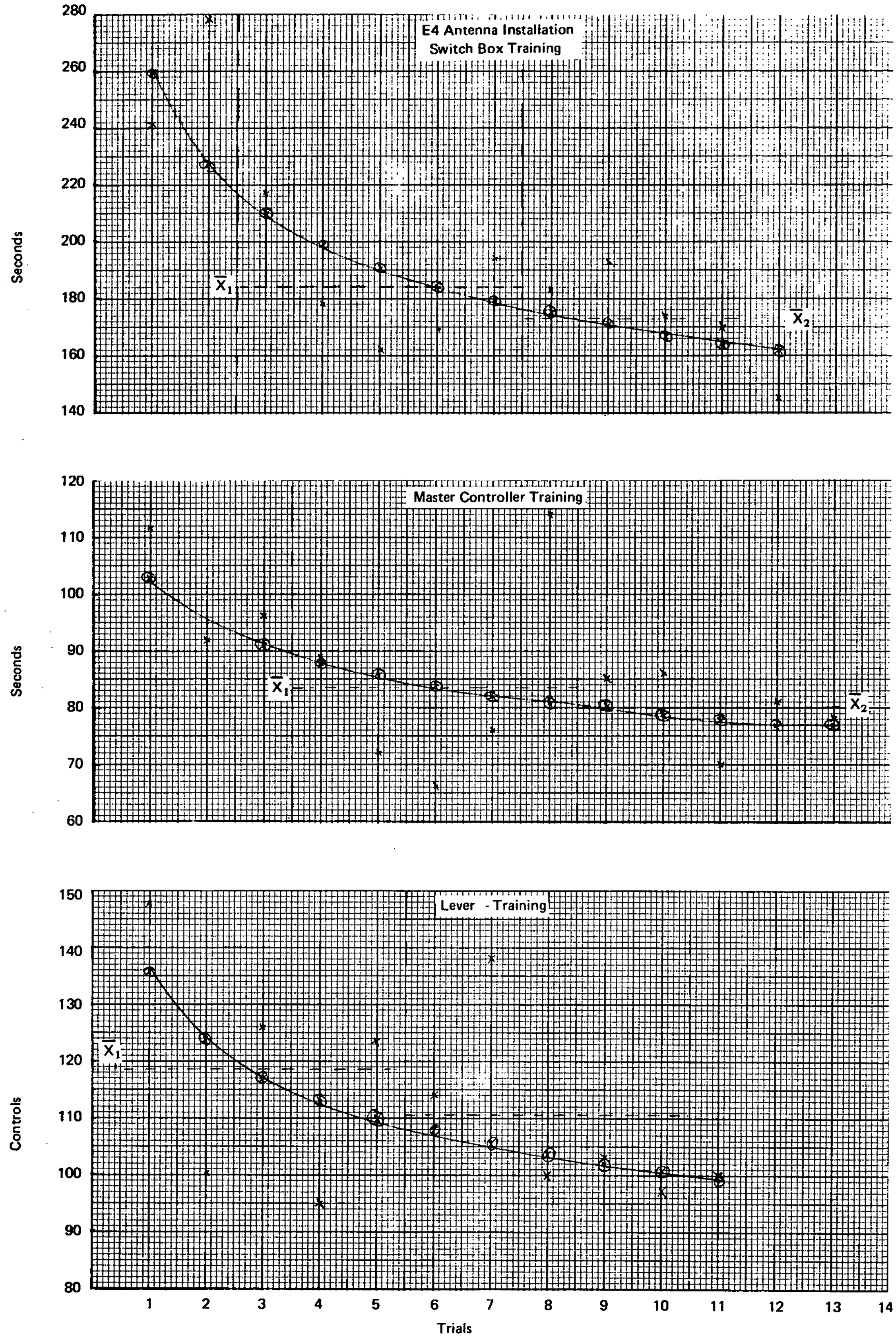
$$|B| \leq t_{\frac{\alpha}{2}}(N)$$

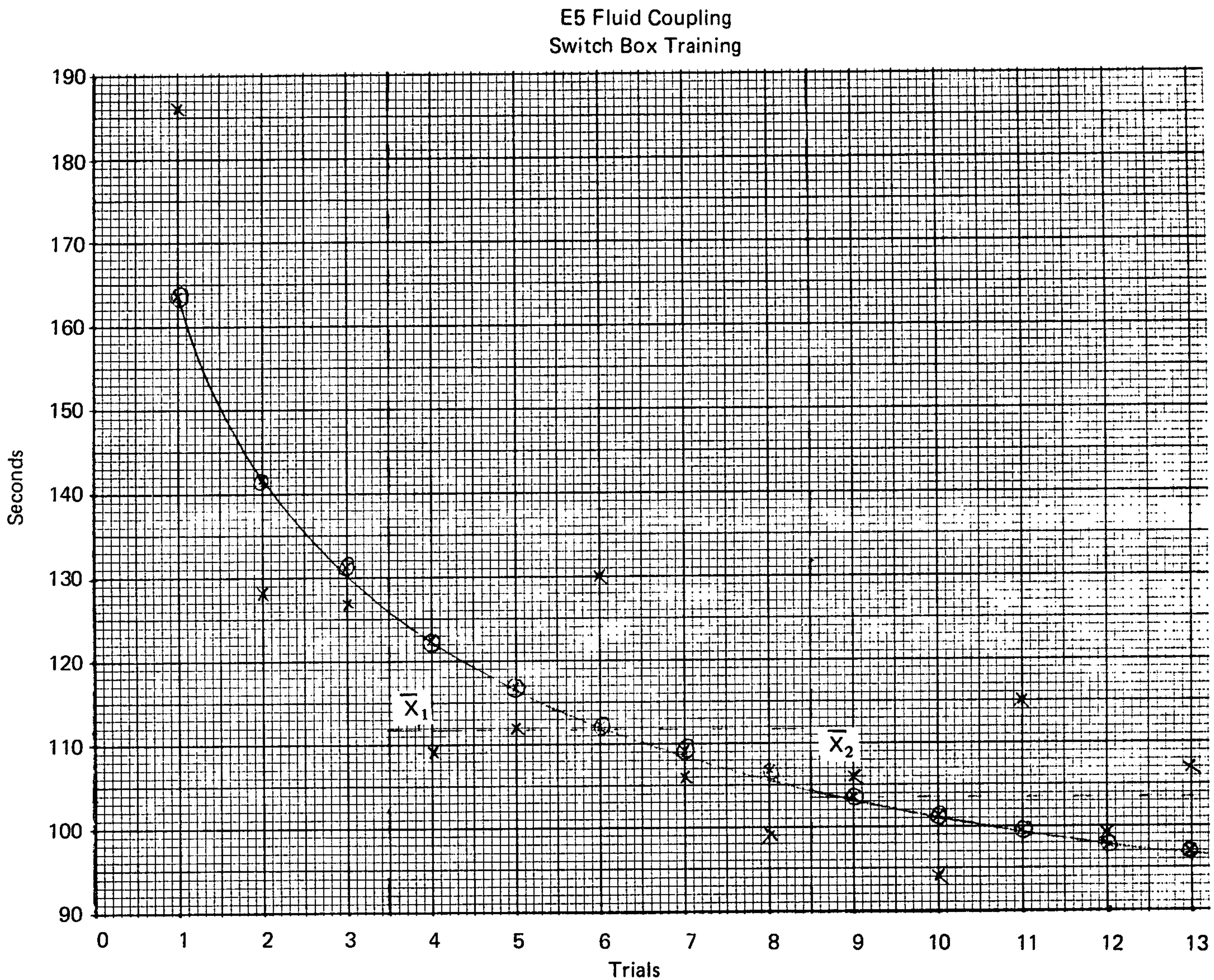

E1 Thruster Replacement
Switch Box Training
Completion Time - Sec
270
260
250
240
230
220
210
$\overline{X}_1$
$\overline{X}_2$
Master Controller
Training
Completion Time - Sec
120
110
100
90
80
70
60
$\overline{X}_1$
$\overline{X}_2$
Levers - Training
Seconds
270
260
250
240
230
220
210
200
190
180
170
$\overline{X}_1$
$\overline{X}_2$
1
2
3
4
5
6
7
8
9
10
11
12
13
Trials

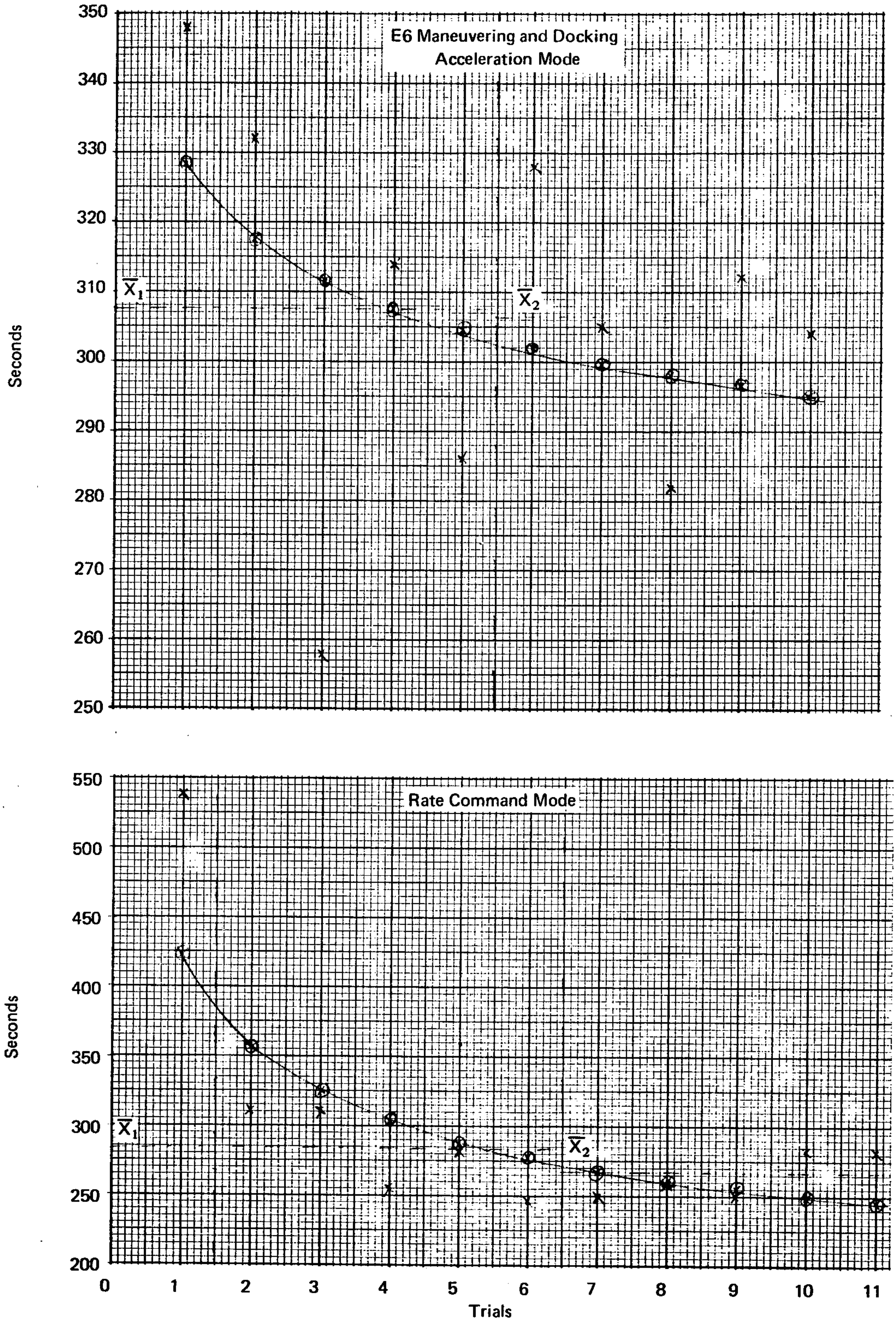

E2 Battery Replacement
Switchbox Training
Seconds
550
500
450
400
350
300
250
$\overline{X}_1$
$\overline{X}_2$


Master Controller Training
Seconds
160
150
140
130
120
110
100
90
$\overline{X}_1$
$\overline{X}_2$
0 1 2 3 4 5 6 7 8 9 10 11 12
Trials


E3 Compartment Inspection
Switch Box Training
Master Controller Training
Levers - Training
Seconds
Trials
$\overline{X}_1$
$\overline{X}_2$


E4 Antenna Installation
Switch Box Training
Seconds
280
260
240
220
200
180
160
140
$\overline{X}_1$
$\overline{X}_2$
Master Controller Training
Seconds
120
110
100
90
80
70
60
$\overline{X}_1$
$\overline{X}_2$
Lever - Training
Controls
150
140
130
120
110
100
90
80
$\overline{X}_1$
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Trials


E5 Fluid Coupling
Switch Box Training
Seconds
190
180
170
160
150
140
130
120
110
100
90
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Trials
$\overline{X}_1$
$\overline{X}_2$


E6 Maneuvering and Docking
Acceleration Mode
Seconds
350
340
330
320
310
300
290
280
270
260
250
$\overline{X}_1$
$\overline{X}_2$
Rate Command Mode
Seconds
550
500
450
400
350
300
250
200
0
1
2
3
4
5
6
7
8
9
10
11
Trials